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JAN 78 S S COOPER, W A BIEGANOUSKY

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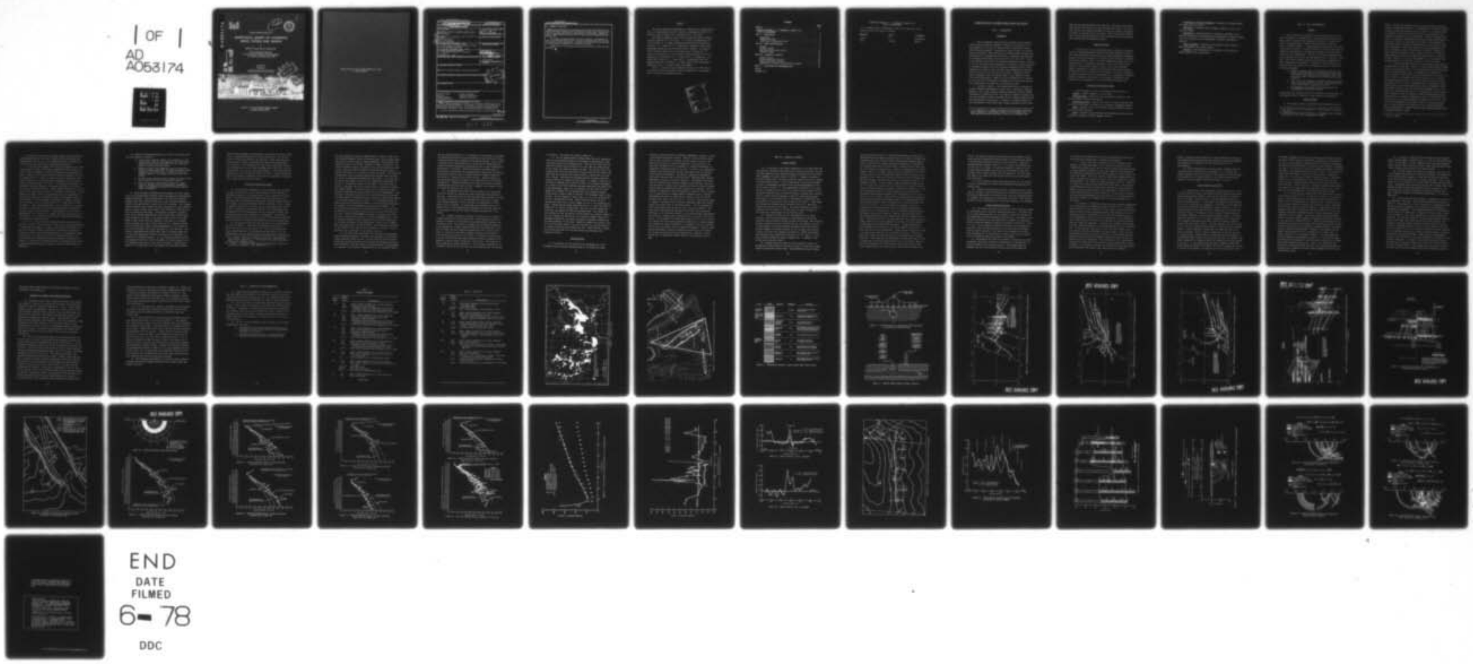

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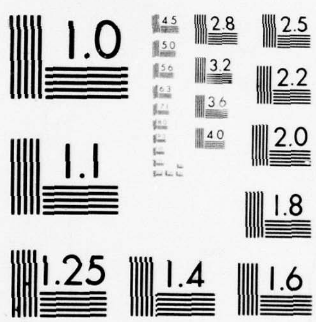

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GEOPHYSICAL SURVEY OF CAVERNOUS AREAS, PATOKA DAM, INDIANA

by

Stafford S. Cooper, Wayne A. Bieganousky

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Three selected geophysical methods, i.e., acoustic, resistivity, and infrared techniques were applied to the problem of solution cavity detection and delineation at Patoka dam site. The infrared technique was abandoned after early efforts indicated it would not prove successful in this application.

Both the acoustic and resistivity methods, however, yielded results over

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20. ABSTRACT (Continued).

The general severity of solutioning activity could be surmised from the resistivity profile produced using the Wenner electrode array. Specific features were further defined using a modification of the Bristow resistivity survey. These features, however, have not been verified by exploratory drilling thus far.

The acoustic technique employed was very successful in delineating the trend of subterranean features for a distance of approximately 200 feet from the location of the energy source. Exploratory drilling proved the existence of several features indicated by the acoustic technique.

A comparison of the electrical resistivity and acoustic results was very favorable.

PREFACE

The cavity detection investigation of Patoka Dam was authorized by the U. S. Army Engineer District, Louisville, Kentucky, in IAO No. DC-B-77-171, dated 10 August 1977, Appropriation No. 96 x 4902.

The field investigation was conducted during the period 23 August through 9 September 1977, by Messrs. J. C. Ables, Instrumentation Services Division, W. L. Murphy, Engineering Geology and Rock Mechanics Division, S. S. Cooper and W. A. Bieganousky, Geodynamics Branch (GDB), Earthquake Engineering and Vibrations Division (EE&VD). The analysis of the acoustics phase of the investigation was performed by S. S. Cooper. The analysis of the electrical resistivity portion of the investigation was performed by W. L. Murphy and W. A. Bieganousky. The report was written by S. S. Cooper and W. A. Bieganousky under the general supervision of Messrs. J. P. Sale, Chief, Soils and Pavements Laboratory, and R. F. Ballard, Chief, GDB, EE&VD.

COL J. L. Cannon, CE, was Commander and Director of WES during the conduct of this investigation and the preparation of this report. Mr. F. R. Brown was Technical Director.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	25.4	millimetres
feet	0.3048	metres

GEOPHYSICAL SURVEY OF CAVERNOUS AREAS, PATOKA DAM, INDIANA

PART I: INTRODUCTION

Background

1. The investigation reported herein describes the specialized cavity detection studies performed at Patoka Dam, including in situ investigations of the dam site using acoustic, resistivity, and infrared sensing techniques. Attention was recently drawn to the importance of subsurface cavity detection and various methods available for such detection at a Symposium on Detection of Subsurface Cavities held in Vicksburg, Mississippi, during the period 12-15 July 1977. These three techniques were chosen from numerous geophysical methods currently in use for the detection and delineation of subsurface cavities because of information gained from recent Waterways Experiment Station (WES) experience in acoustic tunnel tracing,* and recommendations resulting from an on-site visit on 30 June 1977 by Messrs. Underwood, Office, Chief of Engineers (OCE) and Ballard (WES) in the company of Louisville District personnel. Radar was also recommended but the results of a one day radar investigation (arranged by the Louisville District) were inconclusive, and radar was not subsequently used.

2. As shown in Figure 1, the Patoka Lake project is situated in southern Indiana, approximately 55 miles west of Louisville, Kentucky. Bedrock in this region contains limestone formations which are highly susceptible to solution activity, and numerous limestone solution cavities with attendant piping and collapse of the overlying sandstone have been encountered at the dam site. Problems of a similar nature have been encountered at other Corps dams, notably Gathright and Wolf Creek

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* R. F. Ballard, Jr., "Dynamic Techniques for Detecting and Tracing Tunnel Complexes," Miscellaneous Paper S-77-25, December 1977, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Dams, and the proposed Meramec Park dam site. Preventive and/or remedial measures have proven to be both extensive and costly. In order to take the most cost effective approach to seal such cavities an economical means of delineating them is desired. Thus nondestructive methods such as those discussed herein are more attractive and less costly than other methods such as exploratory boring.

Purpose and Scope

3. The purpose of this investigation was to determine the practicality of using nondestructive means of detecting subsurface cavities. This investigation was conducted using the three geophysical techniques thought to be most applicable to the case at hand, acoustic, resistivity and infrared sensing. Each of the three geophysical methods was first considered from a feasibility standpoint, then if the method showed promise, it was actively pursued; if not, its use was terminated. Partial confirmation of results was obtained by drilling, providing a drilling rig could be diverted for the purpose. This report documents the results obtained in the investigations of the geophysical techniques pursued, including confirmation of the findings, interpretive data analyses, and an assessment of the cavity detection methods used.

Definitions of Technical Terms

4. The following is a list of technical terms used herein:

Anomaly - Unusual reading in a set of data.

Electrode array - Pattern in which electrodes are placed on the ground surface to measure resistivity.

Equipotential bowl - Locus of all points at a given potential near a current source which is located on the surface of homogeneous ground.

Grike - Opening in the top of bedrock; usually caused by solution and often filled with soil.

Karst - Area where earth materials have undergone solution erosion usually in limestone, dolomite, gypsum, or salt.

Potential or electrical potential - Difference in voltage between two points within a circuit.

Resistance - Opposition that a material offers to a flow of an electric current.

Resistivity - Apparent measure of electrical resistance as determined from surface measurements usually expressed as ohm-cm or ohm-ft (not to be confused with the measurement resistance, expressed as ohms/cm^3).

Sink or sinkhole - Depression of the ground surface related to karst development below ground surface.

Traverse - Line established on the surface of the ground and marked comulatively in linear feet.

PART II: FIELD INVESTIGATIONS

General

5. The field work was performed by a four-man WES crew in the period 23 August to 9 September 1977. After consultation with Mr. Ben Kelly, Chief, Geology Section, Engineering Division, Louisville District, the primary area of interest was established as shown in Figure 2 (dashed triangle). A typical geologic sequence in this vicinity is shown in Figure 3. Solution activity in the Glen Dean limestone formation (substantiated by borings and trenching) was the principal concern in this investigation. The area of interest encompassed most of the spillway, part of the left dam abutment, and the west end of the dike. Some heavily wooded areas and other difficult topographic features complicated investigations. Accordingly, the spillway was selected as the first priority for investigation because it offered the following advantages:

- a. Numerous collapse zones in the Mansfield sandstone were exposed during excavation of the spillway to final grade at el 548.* These features were presumed to result from solution activity (cavities) in the underlying Glen Dean limestone.
- b. Only a 5-10 ft** thickness of Mansfield sandstone remained when the spillway was cut to el 548. This favorable condition did not exist elsewhere at the site.
- c. No topographic corrections were required because the spillway had been leveled to grade.

In the event that favorable results were obtained in the spillway, the investigation would be extended to other areas as time permitted.

Acoustic Survey

6. The acoustic method of subsurface cavity detection has been

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* All elevations (el) cited herein are in feet referred to mean sea level (msl).

** A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

proven in earlier WES studies,* but was used only to detect man-made tunnels in overburden materials. The applicability of acoustic surveys to detect solution cavities was yet to be proven. In previous studies to determine a cavity's extent and direction, a high-capacity loudspeaker was placed inside the tunnel mouth. Then, as the speaker was swept up in frequency, measurements were made of peak-to-peak particle velocity of the soil at the mouth of the tunnel. The frequency and signal input level recorded at resonance were held constant for subsequent measurements. The latter particle velocity measurements were made at increasing surface distances from the source. Multiple geophone arrays were typically used, as shown in Figure 4. Because of signal attenuation effects, the maximum effective source to detector distance, using a 12- to 15-in.-diam speaker of 75- to 150-watt power handling capacity, was typically limited to a few hundred feet.

7. A similar procedure was used for the acoustic cavity detection investigation at Patoka Dam. However, a special single channel sensing device was developed by WES for this investigation and was substituted for the multiple geophone array. A schematic of the WES device is shown in Figure 5; this device enabled the operator to take data at the rate of about two data samples per minute (typical for 2 ft spacing between measurement points). This data acquisition rate is at least five times as fast as the rate obtainable with a conventional seismic geophone array, and the WES portable unit enjoys an additional advantage because voltage output from the detector geophone (which is proportional to peak particle velocity) is read directly from the oscilloscope. Because of time limitations, the WES portable amplifier gain settings were not rigorously calibrated in terms of P-P particle velocities prior to this study, although a calibration value of 6.6 volts/in./sec is approximately ($\pm$20 percent) correct for the gain setting used. In this instance the variation was not considered important since the intent was to compare relative signal amplitudes rather than to establish absolute values.

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* Op. cit., page 4.

8. The cavity locations and the peak voltage output recorded at each measurement point are shown in Figures 6-10; the cavities are designated as "A," "B," etc., for identification and to indicate the order in which they were tested, beginning with cavity "A."

9. It was not known whether the 15-in.-diam speakers used by WES could provide a signal of sufficient strength for cavity detection in rock, so the investigation of cavity "A" proceeded on an experimental basis. However, it was discovered that driving the speaker with an input signal level of 1.5 amps, at cavity resonance, did produce sufficient ground motion so that meaningful measurements could be made at source to detector ranges up to 200 ft. Unfortunately, inputting this relatively high level signal to the speaker resulted in its failure after about 4 hours of operation. Minor speaker distortion was audible at all times, and tended to increase in intensity until failure occurred. However, the signal received by the detector was not appreciably affected by the distortion, presumably because of attenuation effects in the rock mass. While the speaker was operating, a number of measurements were made in the area around cavity "A." These data are shown in Figure 6. After some experimentation with the detector, an attempt was made to track signal paths by taking measurements at increasing distances from the source (speaker). Measurements were first made at approximately 2 ft intervals in a roughly concentric pattern about the cavity mouth. Once a data trend was observed, additional measurements were made in the trend direction.

10. Due to the high level of background noise from construction activity, it was at first difficult to identify the source and amplitude of relatively weak signals. Initially, the problem of ambiguous signals was resolved by manually cutting off the speaker and observing whether the signal continued (background noise) or disappeared (signal of interest). The same result was later accomplished using a tone burst generator to automatically pulse the speaker at preselected intervals. In this way the undesirable effects of background noise could be greatly minimized because the signal of interest could readily be identified.

11. Several interesting phenomena were noted in the initial work with the detector, as follows:

<u>a</u>. In most cases, detected signals were confined to a very limited area. That is, the signal was lost when the detector was moved a few inches off line (in a direction normal to the observed data trend).

<u>b</u>. Signals of fairly large amplitude could be traced for a limited distance, after which the signal path might either disappear or shift directions. Usually the shift was about 90 degrees to its original trend direction on the surface.

<u>c</u>. In some locales, signals would be detected at points which did not seem to fall into a decipherable pattern.

<u>d</u>. There was usually a considerable variation in signal levels at adjacent points of measurement, although the signal level generally decreased with distance from the source, as expected.

12. These preliminary findings were encouraging, but were indicative of the interpretation problems usually associated with geologically complex structures. Visual observations of the Glen Dean limestone exposed in the dike trench had shown that joint cracking typically occurred on N-S and E-W axes at about 10 to 20 ft intervals. And, exposed solution features took a variety of forms including thin, open, vertical joints, lateral or sheet type fissures, and horizontal or vertical tunnels of diverse size and shape. The presence of numerous collapsed zones in the spillway sandstone was clear evidence that similar conditions existed in that area; it was equally obvious that a very large number of data points would be required to trace most of the signal paths occurring in an area of about 200 by 200 ft. Complete coverage of such an area would require 10,000 measurements on 2 ft centers and this, while desirable, was neither practical nor cost effective. Conversely, measurements made using larger than 2 ft spacings might fail to locate some significant features, according to the experience accumulated in preliminary testing. So, the original procedure was used to investigate cavities "B" and "C," however, an effort was made to record additional data points in the area of interest. Beginning with cavity "B," a replacement 15-in.-diam speaker was used which proved to

have improved performance characteristics, including an increased output level. A modified procedure was used for cavities "D," "E," and for cavity "F" which was located in the dike area. These areas were surveyed using an irregular rectangular grid pattern with measurements of 2 ft centers. The irregular grid lines resulted primarily from surface conditions such as mud holes, standing water, rock piles, material storage piles, etc., rather than from preference. A final grid pattern acoustic survey was also done at cavity "A," both to acquire additional data and to provide a comparison of the two data acquisition techniques used. These data are shown in Figure 6.

Electrical Resistivity Survey

13. The theoretical background for the techniques used is beyond the scope of this report, but is well documented in the literature. Background information is provided herein only for purposes of clarification. Electrical resistivity methods have been widely used for a broad spectrum of geotechnical applications, including cavity detection. The rationale for using electrical resistivity methods is that a cavity in limestone, whether it is filled with air, water and/or soil, should exhibit a resistivity contrast with respect to the surrounding rock. In planning for this investigation, the cavity detection methods used by Bates* and others were considered for employment. The modified Bristow technique, as used by Bates, and the well known Wenner method** were selected for use because they appeared to be the most promising.

14. The various resistivity lines surveyed in this investigation are shown in Figure 11. The Bristow technique was used only on a 245 ft section of line 1 near cavity "A." Its use was discontinued because interpretations of field data raised some doubts as to its effectiveness, and also because greater coverage could be obtained in

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* E. R. Bates, "Detection of Subsurface Cavities," Miscellaneous Paper S-73-40, June 1973, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

** F. Wenner, "A Method of Measuring Earth Resistivity," Bulletin of the Bureau of Standards, 1916, Washington, D. C.

the time available by using the Wenner method. However, results of a more detailed analysis, which are presented later in this report, indicate that the Bristow data are indeed meaningful. The electrode configuration used for the Bristow technique is shown in Figure 12. One current electrode (source) was placed on the survey line and the other current (sink) electrode was placed at effective infinity, which is usually defined as 5 to 10 times the survey line length. This electrode configuration ideally produces equipotential surfaces which surround the source in approximate hemispherical bowl shapes. It is this characteristic which permits the use of the graphical interpretation described in the analysis section of this report. The shaded area in Figure 12 represents the zone of material that is assumed to influence the surface reading. It should be noted that in reality all nearby subsurface conductivities also influence the surface measurement. With the source electrode in position on the survey line and with the sink electrode located at effective infinity, potential readings were made at 5 ft intervals along resistivity line 1. A 5 ft spacing between the Bristow potential electrodes was deemed to provide adequate resolution for purposes of this investigation, and was used throughout. Four source electrode positions were selected along line 1, and these were as follows; C_1 at sta 0+00; C_2 at sta 0+50; C_3 at sta 1+00; and C_4 at sta 1+50. Potential measurements were made, as required, both north and south of each source location to provide overlapping data. Plots of the data obtained at each successive source location beginning at C_1 are shown in Figures 13-18, respectively. Figure 19 is a summary plot which shows all of the Bristow data. Other information pertinent to the analysis of the data are also included on the plots. This information will be discussed in the analysis section.

15. The bulk of the resistivity work was carried out using the Wenner profiling technique. The Wenner array consists of four evenly spaced electrodes placed in line. In this study the outer two electrodes were current electrodes, and the inner pair measured the potential difference. With this array, the effective depth of investigation is a function of the relative conductivities of the subsurface layers,

and the electrode spacing "a." The greater the "a" spacing, the greater the penetration depth for a given subsurface profile and also the larger volume of material that influences the potential reading. Thus, a depth of interest can be investigated over a large area by establishing the required electrode spacing and profiling the area on some predetermined grid pattern. To obtain a resistivity profile, the Wenner array is moved along an established line, maintaining the same electrode spacing. The distance that the array is shifted along the traverse between observations is a function of the detail desired. Readings taken this way are plotted along the traverse at the centerpoint of the electrode configuration. Subsurface anomalies are sought in the form of sharply contrasting resistivity highs or lows as compared to an average or base line value of resistivity for the line.

16. Two general areas, that of the spillway and the area along the 560 ft contour line between the dike and spillway were profiled in this way. It was known that the Glen Dean-Hardinsburg interface occurred at a depth of about 35 ft in the spillway area, and a rule of thumb (with varing acceptance) is that the depth of investigation is about equal to the "a" spacing. To investigate the assumption that an "a" spacing of 30 ft would significantly penetrate the Glen Dean limestone, it was decided to perform two Wenner soundings perpendicular to one another.

17. A Wenner sounding is performed by varying the "a" spacing in a Wenner array about a fixed center point. This technique is used to identify the depths at which layers having substantially different conductivities occur. The purpose of running two soundings perpendicular to one another was to detect lateral differences in resistivity, if any. Both the Wenner and Lee sounding techniques were used. The Lee technique is a variant of the Wenner sounding technique which requires a fifth electrode, positioned in the center of the Wenner electrode array. It allows left hand and right hand potential difference readings and is employed to detect lateral variations in resistivity. The locations of these soundings are shown in Figure 11. The N-S Wenner sounding had its centerpoint located at sta 102.5 and the E-W sounding center was located

at sta 202.5. The results are shown in Figure 20.

18. The two perpendicular soundings agree very well, indicating that the area influencing these two soundings has approximately equal electrical conductivity characteristics. This does not imply that the areas are without solution features, but only that the average resistivity values with depth are nearly the same. The results of the first sounding with the Lee modification are also plotted on this figure, and these data also indicate very similar trends in resistivity as a function of depth. The second Lee sounding produced virtually identical results, and was not plotted for this reason. A change in slope of the resistivity sounding curves occurs at about 40 ft in depth, presumably as a result of the lower resistivity usually associated with shales such as the Hardinsburg. Hence, an "a" spacing of no more than 30 ft was judged to be optimum for the spillway area, since greater spacings would involve a larger volume of material, with attendant losses in resolution. The full length of survey lines 1, 2, and 3 was profiled with the 30 ft spacing Wenner array. Wenner profiles using 5 and 20 ft spacings were also run on a short segment of line 1, for comparison purposes. Wenner profiles along resistivity lines 1, 2, and 3 are shown in Figures 21, 22, and 23, respectively. Both 30- and 50-ft Wenner profiles were run between the dike and spillway areas. The location of this resistivity line and earlier boring locations are shown in Figure 24. The 50 ft spacing was selected so as to achieve a greater depth of investigation because of the greater thickness of material overlying the Glen Dean formation in that area. Figure 25 presents the results of the 30- and 50-ft Wenner surveys, and also indicates the relative position of borings located near the resistivity line. Figure 26 shows a subsurface profile developed from air-trac boring logs provided by the Louisville District.

Infrared Survey

19. In planning for the infrared field investigation, it was recognized that an airborne infrared sweep of the Patoka site might

provide, through detection of subsurface temperature contrasts, a means of delineating subsurface cavities. However, because airborne sweeps had not been successful in the past in other areas, and such an airborne mission would be relatively expensive, it was decided to use hand held instruments first to determine if infrared measurements of temperature contrasts existed at the site. If little or no temperature contrasts were obtained with hand held instruments then the airborne mission could be eliminated. Accordingly, temperature measurements were made at various times of the day using a calibrated Wahl infrared thermometer (accurate to within ± 1 degree C). Measurements were made both at the points where acoustic vibrations were detected, (and cavities were known to exist) and at numerous other points along the ground surface where no significant ground vibrations were detected. No differences in temperatures could be detected at suspected cavity locations such as along joints or between apparent limestone joints. Repeated measurements were made to verify this at different times of the day including 0430, 1000, 1400, and 1700 hr. Shifts in wind patterns caused a 1 degree C, variation from a previous measurement taken only seconds sooner at the same point on the ground surface. All the temperatures read at each time of the day did not vary more than ± 1 degree C, and these minor differences were attributed to shifts in wind speed and direction, or to local water puddles on the surface whether measurements were taken at a detected joint, between joints or even over the cavity itself. It was thought that measurements made at 0430 hr on the morning of 25 August 1977 would show significant differences in surface temperatures because the period 0300-0530 hr is regarded as the most favorable time of the day to detect surface temperature anomalies. However, early morning measurements showed no temperature differences for a complete set of data collected around the collapsed zone. Therefore, it was decided that no additional thermal detection investigations would be made.

PART III: ANALYSIS OF RESULTS

Acoustic Survey

20. It was known, from visual observations in the dike trench and from geologic information furnished by the Louisville District, that the Glen Dean limestone joint patterns generally followed E-W and N-S lines. Field judgements of early results on cavity "A," seemed to indicate a N-S and E-W data trend. The major trend for cavities "B" and "C" seemed to be more NE-SW, however. This interpretation was verified by making a series of measurements along E-W lines located approximately 50 and 100 ft south of cavity "C." Such measurements were made at 1 ft intervals for a distance of more than 100 ft on each side of cavity "B," although the locations were not recorded because no signals were received. Since no signals from the speaker in cavity "B" were received along these lines, it was concluded that no N-S feature of significant size was present in the area just south of cavities "B" and "C." Some signal path tracing was attempted while surveying cavity "E." These very limited data indicate an E-W trend. The results obtained on cavity "F," located in the south wall of the dike trench as shown in Figure 10, also indicates a predominant N-S and E-W data trend.

21. Because the intent of this investigation was to detect cavities in the Glen Dean limestone, it was desired to confirm the acoustical cavity detection results by means of drilling. The Louisville District provided an air-trac drilling rig for this purpose, but only a limited amount of drilling time was available because this rig was actively engaged in shothole drilling for the spillway cutoff trench. A total of 12 holes were drilled in an effort to confirm the acoustic and resistivity data obtained near cavities "A," "B," and "C." Locations of these borings are shown in Figures 6-10. A summary of the boring logs is shown in Table 1.

22. Borings B1-B4 were drilled in the vicinity of cavity "C." Borings B5-B7 were drilled in the area of cavity "A," and were located along the resistivity survey lines. Borings B8-B12 were also located

in the vicinity of cavity "C." Boring B4 penetrated a cavity at the Mansfield-Glen Dean contact, between 6 and 8 ft in depth. Borings B1-B3 penetrated some thin soft zones and the cuttings were reddish brown in color to about 15 ft in depth, indicating weathering of the limestone and possibly some minor mud filled voids. Borings B6 and B7 were similar in character to borings B1-B3. Boring B5 encountered hard limestone between 2 and 30 ft in depth (bottom of hole); cuttings from this borehole were white in color (unweathered limestone) and drilling was comparatively slow. While only boring B4 revealed a cavity, borings B1-B3 and B6-B7 strongly indicated the presence of solution activity in the immediate vicinity. It was decided to make additional borings at cavity "C" because the driller recalled drilling into a cavity in that vicinity in earlier exploratory borings. Boring B8 was drilled at a location corresponding with the drillers recollection, and this boring encountered very weathered limestone with occasional minor soft zones from 7 to 13 ft in depth. Boring B9 was located closer to an area more densely populated with acoustic data points. This boring encountered very weathered limestone with occasional soft to very hard lenses from 6 to 13 ft in depth. At 13 ft in depth in boring B9 a tool drop occurred, and no bottom was found to 30 ft in depth, indicating the presence of a 17 ft deep cavity. Only a few acoustic measurements had been made in the area of boring B9. However, available data points did indicate NE-SW trend so the remaining borings were located accordingly. Boring B10 was offset from the indicated line and was located in an area where acoustic data suggested the presence of a NW-SE feature intersecting the principal NE-SW data trend. Slightly weathered to hard limestone was encountered in boring B10 between 6 and 20 ft in depth, and the hole was discontinued. Boring B11 was located 8 ft south of boring B10 and directly over an acoustic data point. Relatively high level signals had been recorded in this vicinity along a roughly NE-SW line. Hard limestone was encountered in boring B11 from 6 to 8 ft in depth, and a tool drop occurred from 8 to 21 ft in depth. When removed from boring B11 the drill pipe was coated with wet, red brown clay, indicating that this cavity was wet and at least partially soil

filled. The acoustic data and boring results both indicated a cavity whose path was northeastward from boring B11 so boring B12 was located on the outermost acoustic data point in that direction. Boring B12 encountered hard limestone from 6 to 7 ft in depth, and cavities from 7-10 and 9-13 ft in depth. The hole was stopped at a depth of 20 ft, in hard limestone because the air-trac rig was needed for shot hole drilling, and no further borings could be undertaken. The drill pipe was found to be coated with red clay mud and water upon final removal from boring B12.

23. Even though the boring confirmation effort was very limited in scope, the borings did confirm field interpretations made from the acoustic data.

24. Detailed interpretations offered in Figures 6-10 were subsequently developed. These interpretations are derived from the patterns and relative amplitudes of the acoustic data, and were originated based on judgement, and experience in interpreting field data. The relative accuracy of these interpretations in large part remains to be confirmed.

Bristow Resistivity Survey

25. The Bristow data shown in Figures 13-19 were plotted as apparent resistivity versus electrode position along line 1. The next step in the interpretation process is to identify the trend of the data and any significant resistivity anomalies that may exist. Any high- or low-resistivity anomalies that are identified are plotted on a subsurface profile, using the graphical technique illustrated in Figure 27. Zones A, B, and C in the simplified example are arrived at by striking arcs having the source electrode position as the center and the distances from the source electrode to the limits of the anomaly as the radii. Zones determined by the intersection of three or more arcs are considered to describe the depth and extent of the anomaly.

26. Establishing the trend of the data is a crucial step in this interpretive procedure, because the determination of high and low resistivity depends upon the trend selected. The average trend and bandwidth for all of the Bristow data was obtained from Figure 19.

The trend of each individual "run" was also determined and plotted together with the average trend, on Figures 13 through 18.

27. From an inspection of Figures 13-19, two important facts emerge: (a) there does appear to be a fairly well defined trend or bandwidth of limited extent, and (b) there are some substantially higher or lower apparent resistivity values, even compared to the bandwidth. Two plausible interpretations are offered, based on arbitrary upper and lower data bounds. The first, and most conservative interpretation was done by choosing only high and low values that fell outside the average data bandwidth. The results are shown in Figures 28 and 29. Figure 28 is a plot of the zones showing high resistivity values. The stippled zone represents the zone of earth which contained the high resistivity anomaly; the black zones formed by the intersection of three or more zones indicate possible air-filled cavities. The locations of the features are given approximately by the locations of the intersections and the size is thought to be roughly equal to the area enclosed by the three zones.

28. Zones with resistivity values that were considered anomalously low as compared to the bandwidth are shown in Figure 29. A low resistivity value can be an indication of a soil, mud, or water-filled cavity. There are few low values resulting from this interpretation, and in no instance is there a zone defined by more than two intersecting arcs. This interpretation, however, is very conservative from the standpoint that so many high and low resistivity anomalies were discounted because they fell within the bandwidth. A somewhat more liberal interpretation was made, taking advantage of the trends established for each individual run. In this instance, high and low values that were judged to obviously deviate from the individual trend were plotted. The points that were plotted have been noted with an asterisk. The graphical interpretations for the high and low anomalous resistivity values are given in Figures 30 and 31, respectively. The intersection of two shaded zones has been left blank and the intersection of three shaded zones has been indicated. It is apparent that when the bandwidth criterion was imposed, the interpretation was biased toward high resistivity anomalies.

However, using the second criterion (a trend established for each run) the interpretation becomes biased more toward low resistivity anomalies. This emphasizes the importance of the trend selection on the interpretation.

29. Other interpretations can also be made, although these two interpretations are believed to be reasonable. It is evident that numerous features have been indicated by the modified Bristow technique. Their actual size or location may not be the same as that predicted because of the very complex structural geology of the site.

Wenner Resistivity Profiles

30. Profile line 1 was established as shown in Figure 11. It is the same location as that of the modified Bristow survey and the North-South trending Wenner sounding. This line was profiled, at least in part, three times. The Wenner 30-ft electrode spacing was used for reasons discussed earlier. As discussed, one segment was also profiled at 5 and 20 ft spacings, for comparison. The results of profiling this line at the three electrode spacings are shown in Figure 21. The 5 ft spacing provides only a shallow depth of penetration, and results were influenced mostly by variations in the top layer of highly fractured and friable sandstone. Air-trac borings performed later in the survey revealed a variable (2 to 6 ft) depth of sandstone in this area, and this, together with material and water content variations, probably accounts for the erratic results. Profiles obtained along line 1 using the 20- and 30-ft electrode spacing exhibit a much less eratic behavior. However, a close examination reveals that the highs and lows do not always correspond. This is almost certainly due to the fact that the 30 ft spacing has a greater depth of penetration and hence averages a considerably larger volume of material than does the 20 ft spacing. The Wenner sounding does confirm the base line resistivity for each spacing at sta 102.5. It was observed that the Wenner sounding results indicated resistivity values of 540 Ohm-ft for the 20 ft spacing and 760 Ohm-ft for the 30 ft spacing. At location 102.5 (the center point of the

N-S Wenner sounding) the 20 and 30 ft profile lines also give resistivity values of 540 Ohm-ft and 760 Ohm-ft, respectively. The results of the line 1 profile seemed to indicate that the resistivity highs might be indicative of shallow depth of burial air-filled cavities. Resistivity lows, on the other hand, were not as sharply contrasting. Profiling continued in the spillway with profile lines 2 and 3. The locations of these lines were offset to the west by 50 and 100 ft, respectively (Figure 11). The results are shown on Figures 22 and 23. The Wenner profile of line 2 was similar to line 1 in resistivity contrasts. Line 3, however, indicated greater resistivity contrasts than either of the other lines. Since lines 1 and 2 crossed the acoustic data spread, it was decided to locate exploratory borings on lines 1 and 2 rather than line 3, even though line 3 had higher resistivity contrasts.

31. The first air-trac drillhole (B5) was centered over a resistivity high on profile line 2. Its location is shown in both Figures 6 and 22. This borehole encountered competent limestone beginning at a depth of 2 ft and remaining so to a depth of 30 ft. The next two air-trac drillholes were then centered over resistivity lows. Drillholes B6 and B7 were located as shown in Figure 6. These borings were very similar to each other in character, and encountered 6 to 7 ft of soft sandstone followed by weathered (brown) to hard, unweathered (white) limestone to 29 ft in depth. While these borings did not intersect a cavity, the brown stained intervals did indicate some solution activity at the locations of borings B6 and B7. Based on these results it was assumed that the method of profiling with the Wenner array was not able to detect individual solution features, probably because of the large volume of material being averaged. However, it was thought that the Wenner technique might still be a valuable tool to detect zones of solution activity, if not individual features. The area worked has a fairly homogeneous stratigraphic profile, i.e., the beds are nearly horizontal and the thickness of the Glen Dean is believed to be reasonably uniform along the survey line. Hence, it is likely that the resistivity variations observed using the 30 ft electrode spacing are primarily due to anomolous features located somewhere within the Glen Dean Limestone Layer.

32. It should be noted here that the Bristow survey occupied a fairly uniform segment of profile line 1, in terms of resistivity variations. In retrospect, a better comparison might have been developed had the Bristow survey been run on line 3, where some pronounced resistivity contrasts were observed on the Wenner profile.

33. The area between the dike and the spillway was the last locale surveyed using electrical resistivity techniques. The Wenner profiling technique was employed as a time and cost effective method to cover this relatively large area in the time remaining. Also, it was thought to be as effective as any other method in detecting zonal variations. This Wenner profile was run along the 560 ft contour line of the abutment between the dike and spillway as shown in Figure 24. Air-trac borings had been previously made in this area, and they indicated a variable thickness of sandstone ranging from 0 to 33 ft (see Figure 26).

34. As previously discussed, Wenner "a" spacings of 30 and 50 ft were employed in this area. The resistivity profiles are plotted in Figure 25. From Figure 25, it can be seen that the occurrence of high and low resistivity anomalies for the 30 and 50 ft spacings are in reasonably good agreement. The substantial decrease in resistivity at the east end of the survey line is thought to be due at least in part to the presence of a fill area, indicated by air-trac boring AT-30, Figure 26. The air-trac borings in the area record numerous open cavities and soft (mud) zones which must be soil-filled cavities. The resistivity profiles likewise indicate extensive zones of solution activity. Comparing Figures 25 and 26, it can be seen that the locations of borings AT-4, 14, 18, 23, and 25 coincide with broad resistivity lows recorded using the 50 ft Wenner electrode spacing. The 50-ft Wenner electrode spacing provides a greater depth of investigation than the 30 ft spacing and is also less influenced by variations in the overlying sandstone. It is again interesting to note that there is generally good correlation between the 30- and 50-ft profile results, in terms of general trends. This suggests that the solution zones in this area involve both the Mansfield and Glen Dean members, and that

these zones have sizeable vertical and lateral expressions, which is confirmed by the boring logs.

Comparison of Acoustic and Resistivity Results

35. Resistivity lines 1 and 2 crossed the acoustic data spread near cavity "A," and line 1 intersected the acoustic data spread near cavities "B" and "C," as shown in Figures 6, 7, and 8. These locales provide a basis for comparisons. The acoustic data for cavity "A" indicate several possible solution features cross resistivity line 1 between sta 68.0 and 130.0. The acoustic interpretation presents these features as probable open vertical joints. The resistivity line 1 Wenner profile indicates little contrast in this locale, however, slight resistivity lows occur from sta 0 to 75.0 and from sta 100 to 130. Between sta 75.0 and 100.0 there is an approximate baseline resistivity value of 760 Ohm-ft. Although one might associate the acoustic data with Wenner resistivity lows, the data in this zone are considered inconclusive.

36. Line 2 also crosses the cavity "A" data spread between sta 95.0 and 107.0; the line 2 resistivity profile registers a rather pronounced resistivity low between about sta 100.0 and sta 125.0. A very pronounced resistivity high occurs on line 2 between about sta 60.0 and sta 100.0. Air-trac boring B5 was drilled at sta 80.0 and encountered very hard unweathered limestone between 2 and 29 ft in depth. Boring B6 was drilled at sta 115.0 on line 2. This boring encountered some weathered limestone intervals but no cavity. However, these data suggest a positive correlation between weathering in B6 boring (which was very near but not on the acoustic line indicating a solution feature), a Wenner resistivity low, and the acoustic data. The fact that the borings did not intersect a cavity can be explained by the fact that it is difficult to hit a thin vertical feature with one drilling attempt. In addition, the detailed acoustic interpretation described herein had not yet been performed when the drilling locations were selected. It is concluded that a fair correlation exists between the acoustic and

Wenner resistivity low data in the vicinity of cavity "A." Another opportunity for acoustic and Wenner resistivity comparisons is where line 1 crosses the acoustic data spread for cavities "B" and "C." The acoustic data interpretation indicates a number of possible solution features between about sta 320.0 and 450.0. This interval coincides with a broad, and relatively deep, resistivity low on the line 1 Wenner resistivity profile.

37. It is concluded that a definite correlation exists between the acoustic and the Wenner resistivity profile data, and that this correlation associates solution activity, resistivity lows, and acoustic data.

38. A final comparison can be made using the Bristow resistivity data obtained along line 1 in the area of cavity "A." The acoustic data indicate that a number of solution features, which are interpreted to be primarily open joints, cross resistivity line 1 between sta 69.0 and sta 130.0. Figures 28, 29, 30, and 31 give the Bristow resistivity interpretations for this interval. Figures 28 and 30 show the interpretation of resistivity highs. These apparent high values fall at about sta 53.0, 72.0, 77.5, and 95.0 on resistivity line 1. All of these are centered in blank (no signal) areas of the acoustic data spread, and do not coincide with any zone where the acoustic interpretation indicates solution activity. However, the Bristow resistivity low interpretation offered in Figure 31 is in good agreement with the acoustic data. The low resistivity zones centered at about sta 70.0, 107.0, and 125 fall in areas where the acoustic data (and interpretation) indicate some solution activity has occurred.

39. The foregoing interpretation of the data clearly indicates a positive correlation between resistivity lows, acoustic data, and solution activity.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

40. Three selected geophysical methods (i.e., acoustic, resistivity, and infrared) were applied to the problem of solution cavity detection and delineation at Patoka dam site. The infrared technique was abandoned after early efforts indicated it would not prove successful.

41. Both the acoustic and resistivity methods yielded conclusive results. These results were partially confirmed with a limited number of borings. In addition, a probable correlation between resistivity lows, acoustic data, and solution features was shown. Because of the promising results of this study, continued efforts should be made to perfect these and other techniques to advance the state of the art in cavity detection.

42. In view of the encouraging results obtained, the following recommendations are made:

- a. Louisville District should consider additional field exploration to verify cavity detection interpretations presented in this study.
- b. Consideration should be given to obtain additional acoustic and resistivity data at the Patoka site.

Table 1

Boring Log Summary

Boring No.	Depth Internal ft	Description
B1	0-6	Moist, weakly cemented tan to brown sandstone
	6-8	Weathered, brown limestone
	8-17	Alternating layers of weathered and hard white limestone with occasional minor soft zones
	17-20	Hard, white limestone, hole bottomed at 20 ft depth
B2	0-5	Moist, weakly cemented tan to brown sandstone
	5-6	Soft, wet, reddish brown clay mud, sand
	6-8	Weathered, brown limestone
	8-15	Alternating layers of weathered and hard white limestone with occasional minor soft zones
	15-20	Hard, white limestone, hole bottomed at 20 ft depth
B3	0-5	Moist, weakly cemented tan to brown sandstone
	5-6	Soft, wet, reddish brown clay mud, sand
	6-8	Weathered, brown limestone
	8-17	Alternating layers of weathered and hard white limestone with occasional soft zones
	17-20	Hard, white limestone, hole bottomed at 20 ft depth
B4	0-5	Moist, weakly cemented, tan to brown sandstone
	5-8	Tool drop, loss of return air, cavity
	8-17	Alternating layers of weathered and hard white limestone with occasional minor soft zones
	17-20	Hard, white limestone, hole bottomed at 20 ft depth
B5	0-2	Moist, weakly cemented, tan to brown sandstone
	2-29	Hard, white limestone, one minor soft zone at 15 ft in depth
	29-	Hole bottomed at 29 ft in Hardinsburg shale
B6	0-6	Moist, weakly cemented tan to brown sandstone
	6-18	Hard, white limestone, weathered zone from 12-13 ft in depth
	18-18.5	Soft black shale
	18.5-30	Hard, white limestone
	30-	Hole bottomed in Hardinsburg shale
B7	0-5	Moist, weakly cemented tan to brown sandstone
	5-7	Soft, black shale

(Continued)

Table 1 (Concluded)

Boring No.	Depth Internal ft	Description
B7	7-18	Hard, white limestone with occasional minor weathered zones
	18-18.5	Soft, black shale
	18.5-24	Hard, white limestone, hole bottomed at 24 ft
B8	0-6	Moist, weakly cemented tan to brown sandstone
	6-7	Soft, wet, reddish brown clay mud
	7-20	Weathered, brown limestone to hole bottom at 20 ft depth. Contained occasional minor soft zones
B9	0-6	Moist, weakly cemented tan to brown sandstone
	6-13	Alternating layers of brown and hard white limestone, occasional minor soft zones
	13-30	Tool drop, loss of return air, cavity
B10	0-6	Moist, weakly cemented tan to brown sandstone
	6-20	Hard, white limestone with occasional minor brown (weathered) zones. Hole bottomed at 20 ft in depth
B11	0-6	Moist, weakly cemented tan to brown sandstone
	6-8	Hard, white limestone
	8-21	Tool drop, loss of return air, cavity. Drill pipe coated with red brown mud and water upon removal from hole
B12	0-6	Moist, weakly cemented tan to brown sandstone
	6-7	Hard, white limestone
	7-10	Tool drop, loss of return air, cavity. Drill pipe coated with red brown mud and water
	10-13	Weathered brown limestone, frequent tool drops, small cavities
	13-20	Hard, white limestone, hole bottomed at 20 ft depth

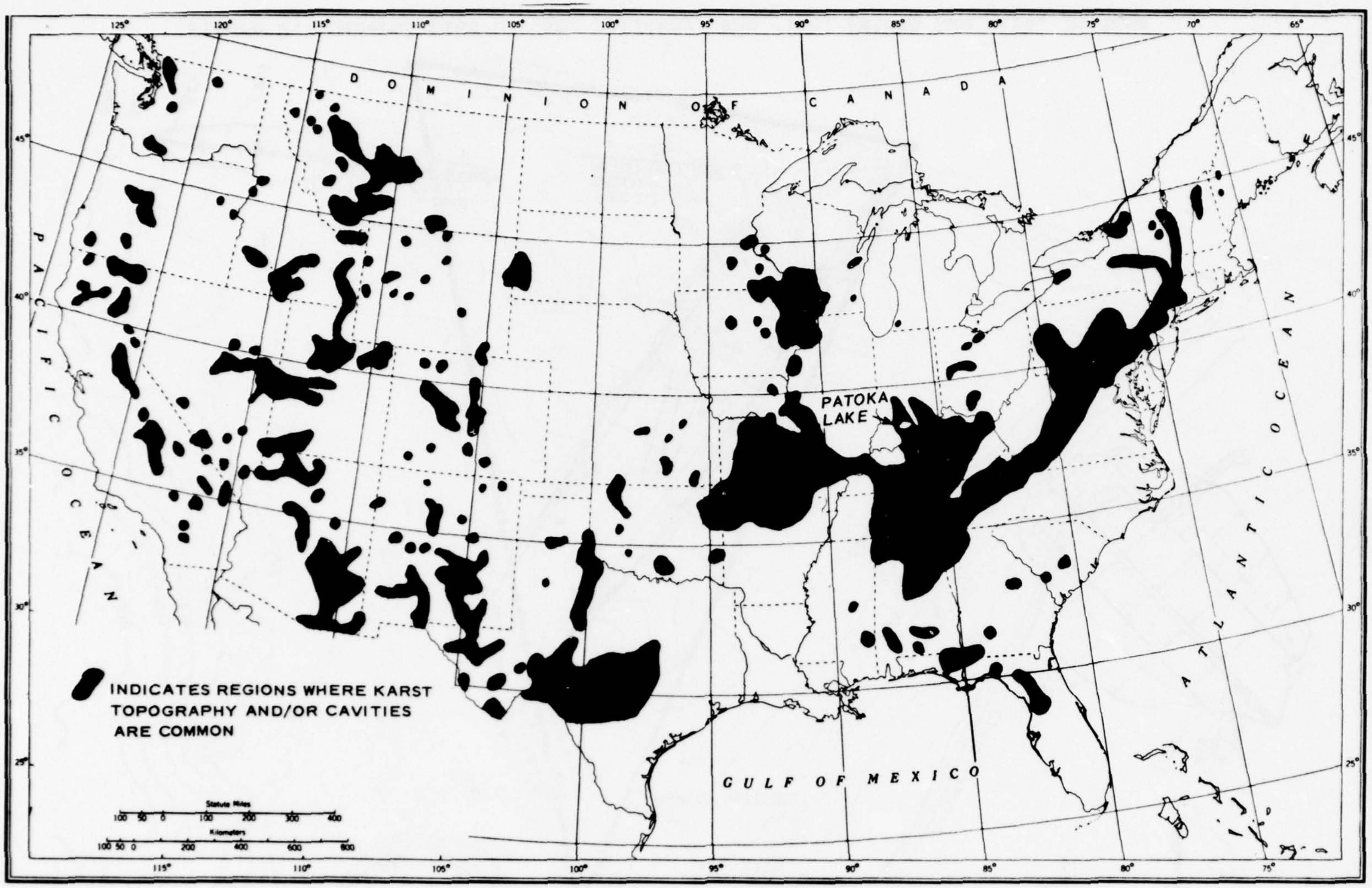

Figure 1. Location of site

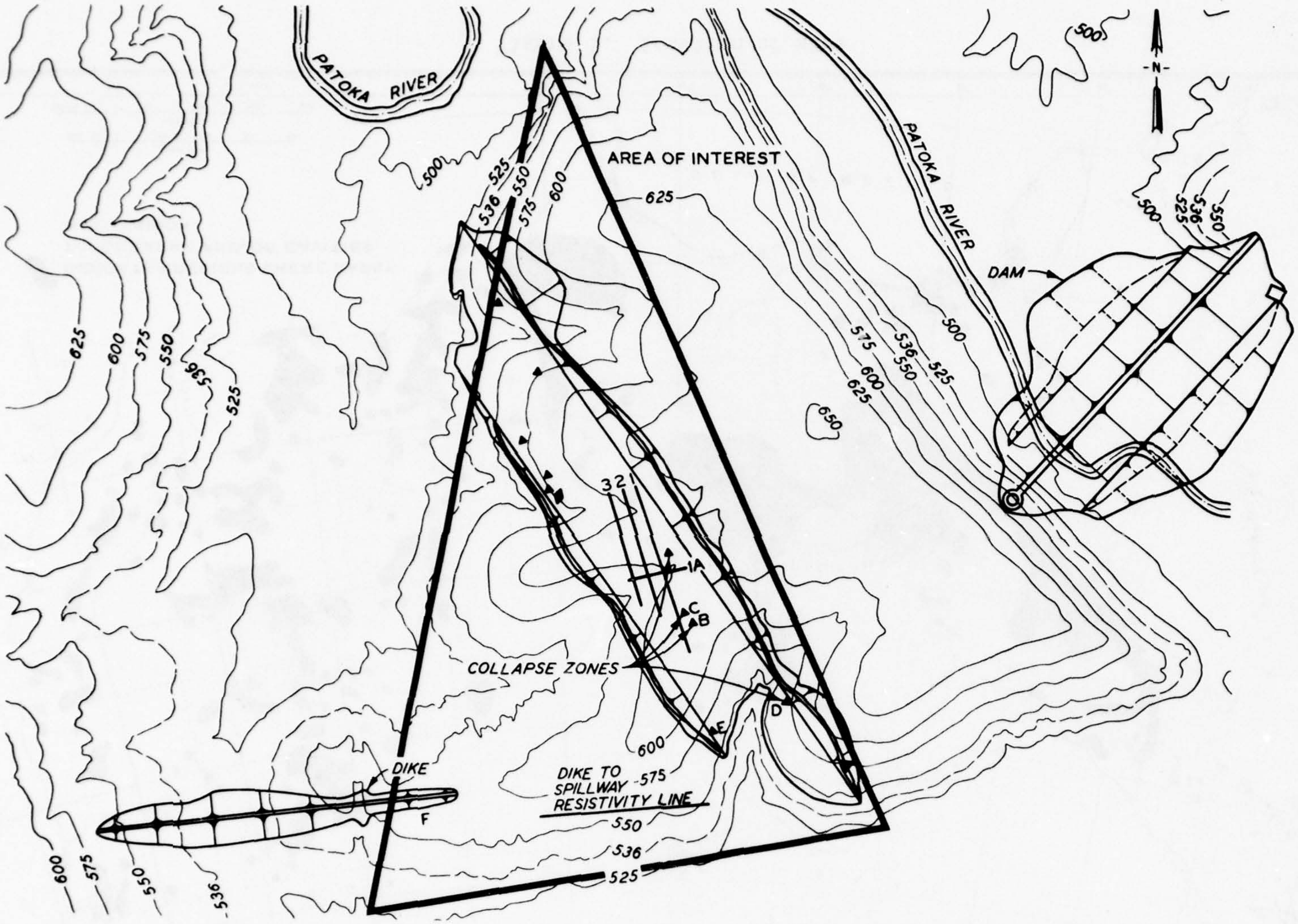

Figure 2. General plan of dam, spillway, and dike, Patoka Dam site, Indiana

AGE	ROCK UNIT	THICKNESS, FT	DESCRIPTION
PLEISTOCENE TO RECENT		VAR 0 - 50 ±	VALLEY ALLUVIUM & LACUSTRINE FINE SAND & SILT
PENNSYLVANIAN (POTTSVILLIAN SERIES)	MANSFIELD FM.	10 - 40	FINE-GRAINED, CROSSBEDDED, FRIABLE SANDSTONE, WITH SANDY SHALES
MISSISSIPPIAN (CHESTERIAN SERIES)	UNCONFORMITY GLEN DEAN LIMESTONE	10 - 30 ±	GRAY, HARD, FINE TO MEDIUM GRAINED, CRYSTALLINE
	HARDINSBURG SHALE	25 - 30 ±	MEDIUM HARD CALCAREOUS SHALE, FAIRLY WELL CEMENTED CALCAREOUS SANDSTONE, & SOFT SLICKENSIDED INDURATED CLAY
	GOLCONDA LIMESTONE	14 - 36	FINE TO MEDIUM GRAINED, CRYSTALLINE
	GOLCONDA SHALE	2 - 20	SHALE - GRAY, CALCAREOUS 1 - 7' INDURATED CLAY AT BASE
	BIG CLIFTY SANDSTONE	35 - 40	GRAY TO WHITE, VERY FINE GRAINED, FRIABLE TO FAIRLY WELL CEMENTED
	BEECH CREEK LIMESTONE	8 ±	FINE TO MEDIUM GRAINED, CRYSTALLINE, ARGILLACEOUS IN LOWER 4'
	ELWREN SHALE	23 ±	REDDISH BROWN, MEDIUM HARD CALCAREOUS SHALE AND INDURATED CLAY

Figure 3. Generalized geologic column, Patoka Lake (after Kelly)

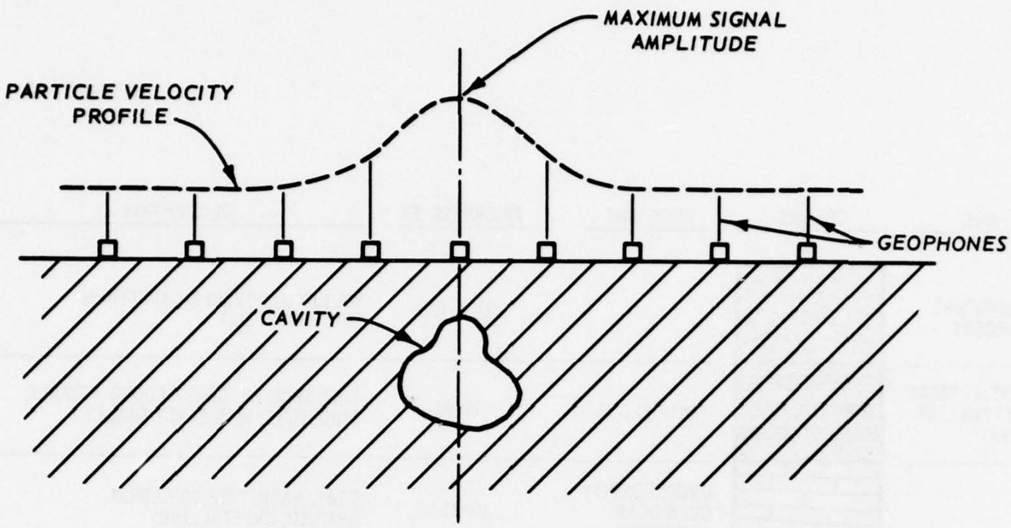

Figure 4. Acoustic method for subsurface cavity detection using multiple geophone array

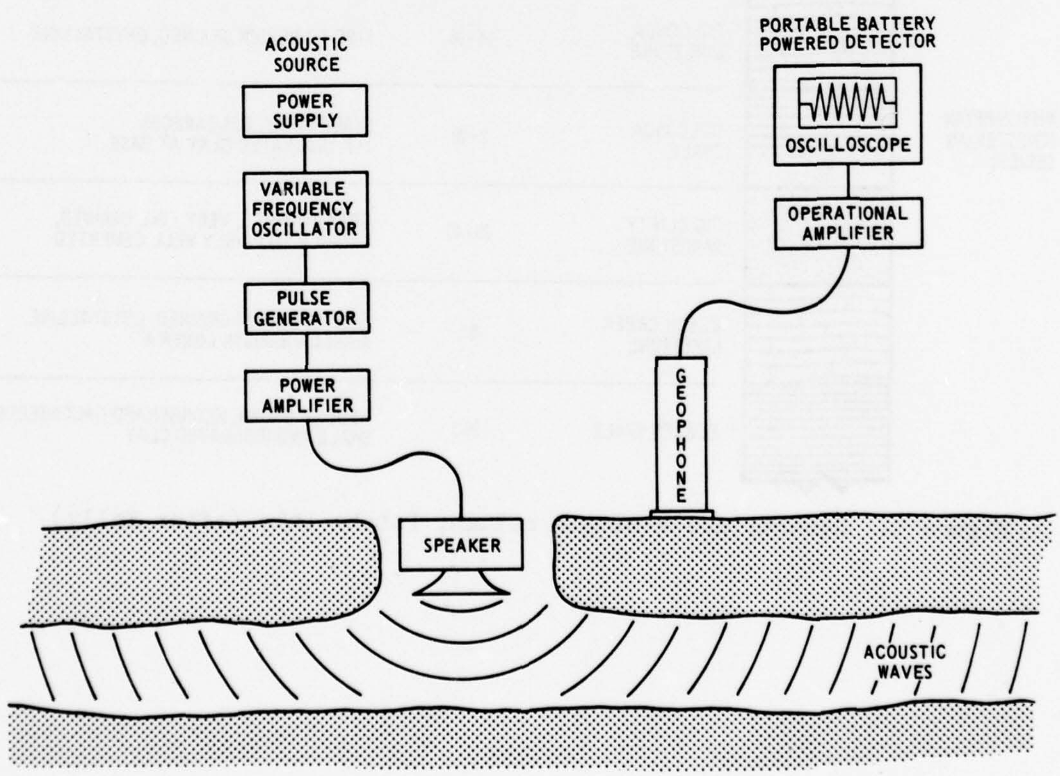

Figure 5. Special single channel seismic detector

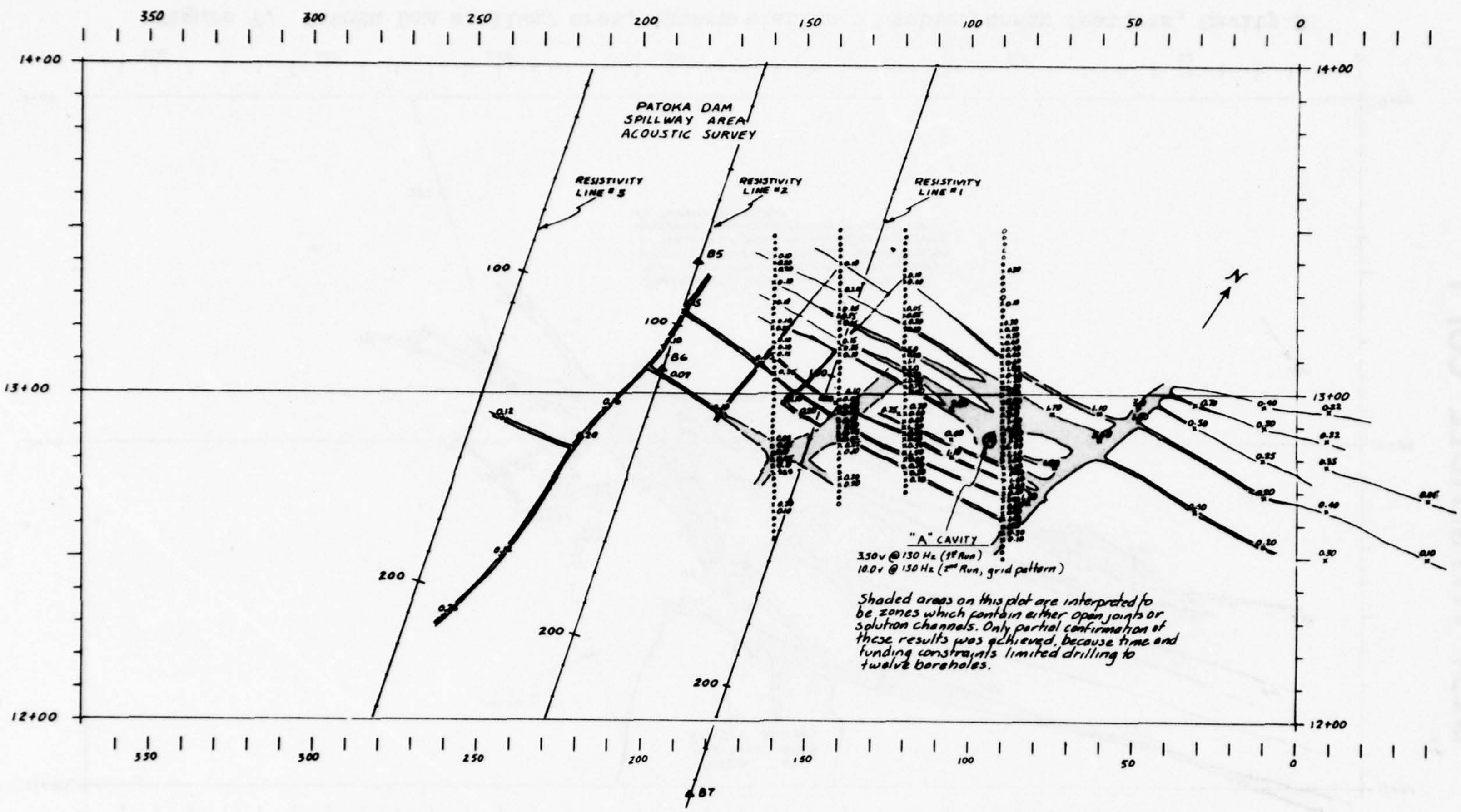

Figure 6. Patoka Dam spillway area, interpretation of subterranean features, Cavity A

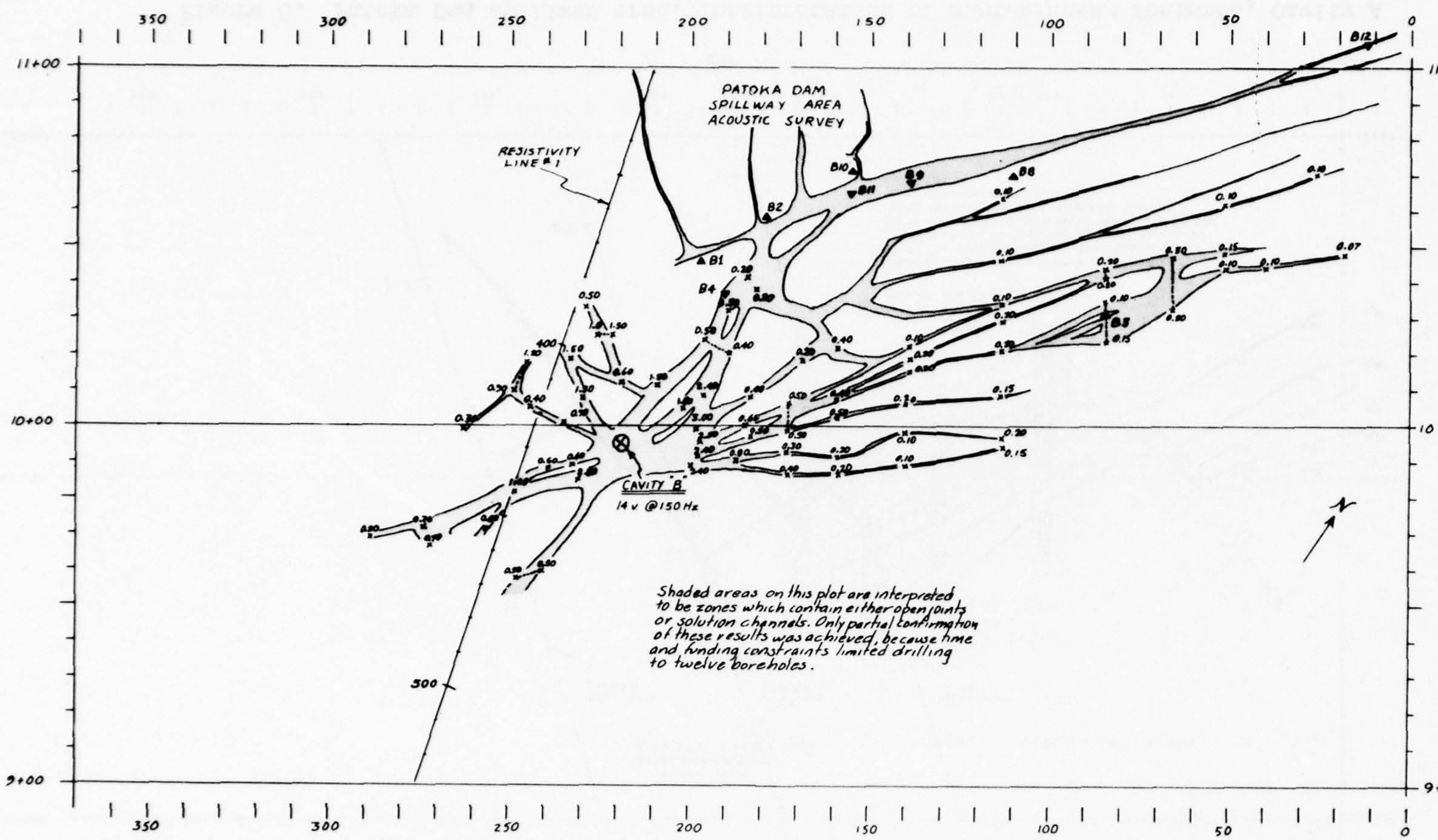

Figure 7. Patoka Dam spillway area, interpretation of subterranean features, Cavity B

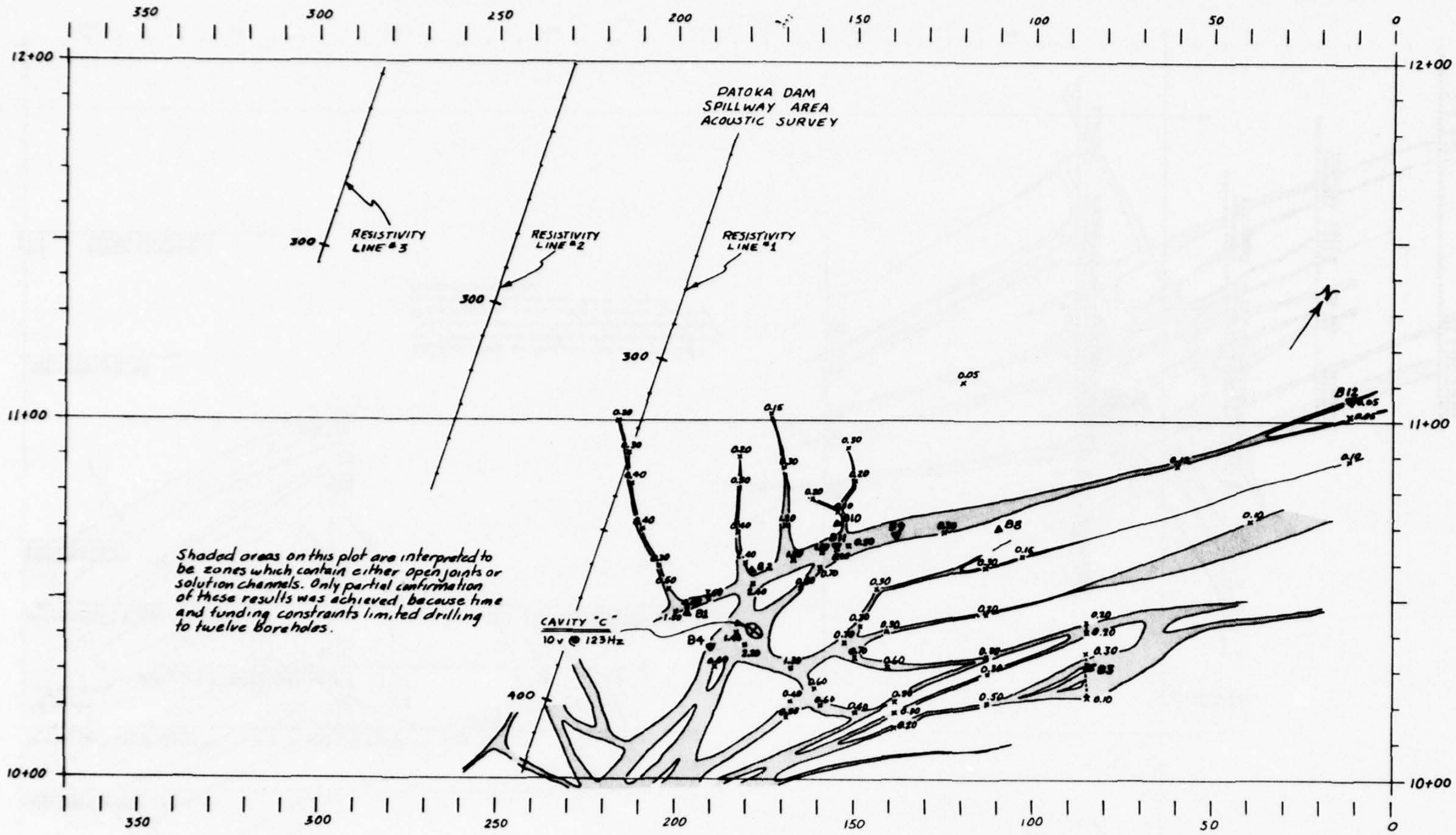

Figure 8. Patoka Dam spillway area, interpretation of subterranean features, Cavity C

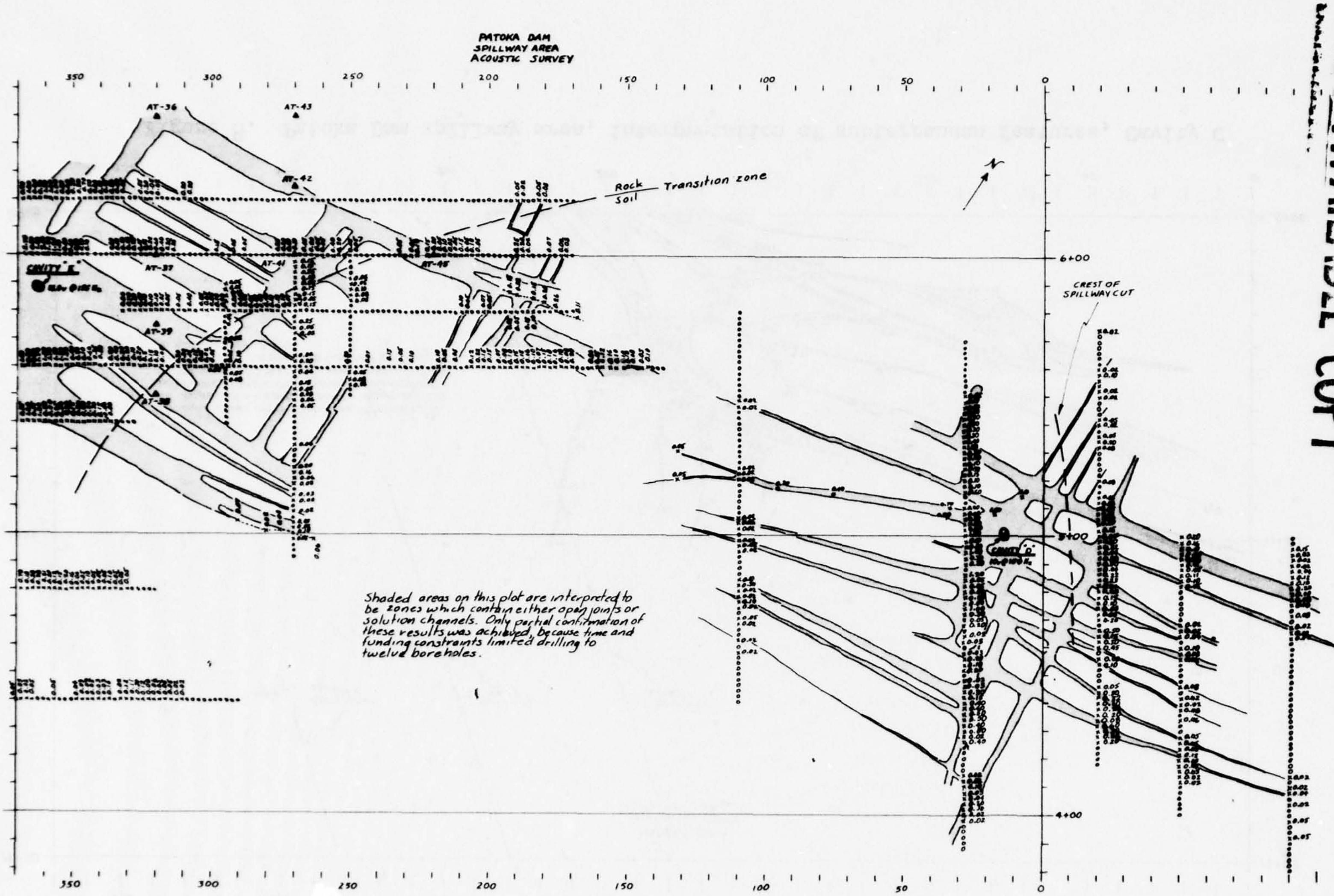

Figure 9. Patoka Dam spillway area, interpretation of subterranean features, Cavity D and Cavity E

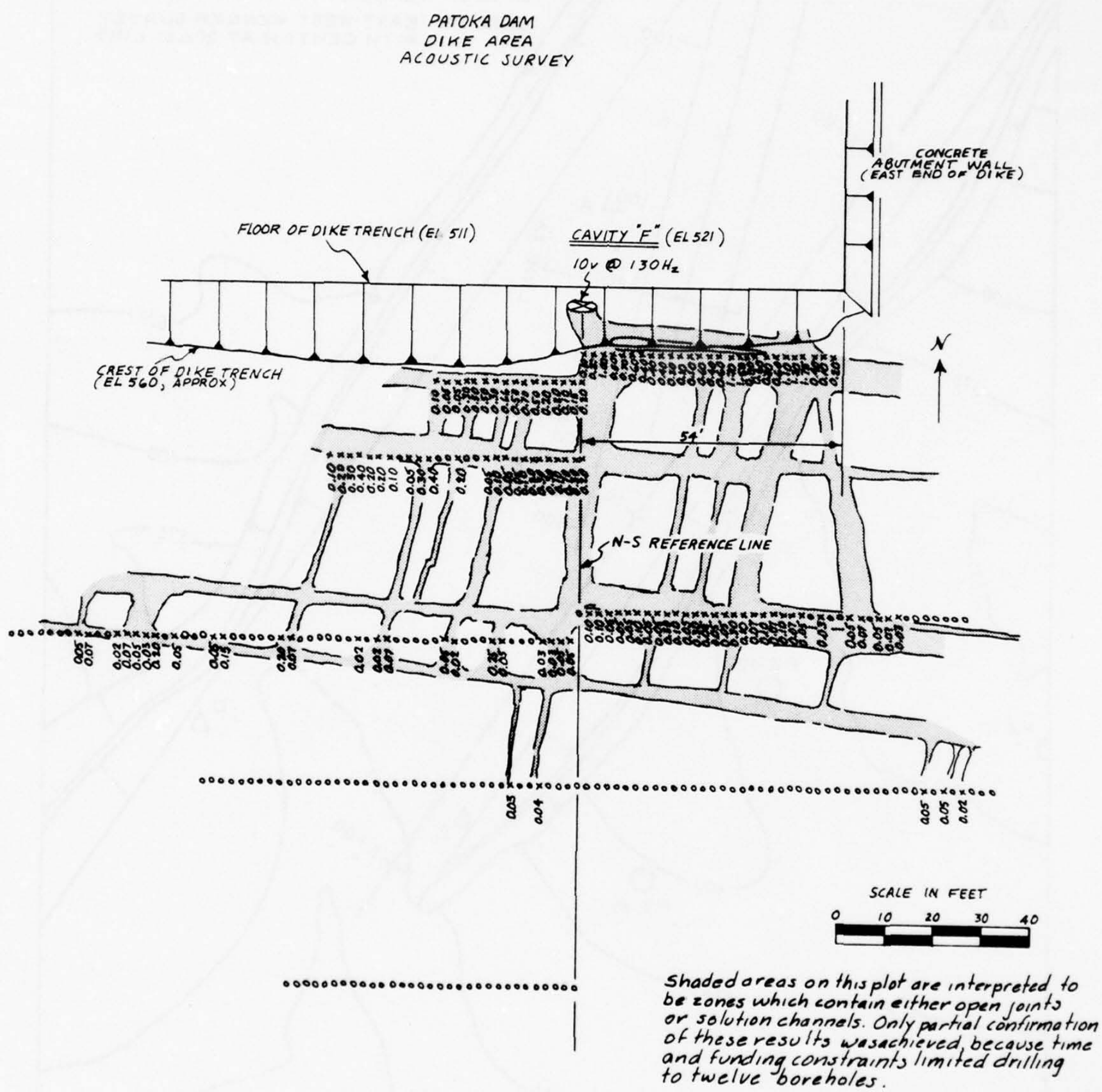

Figure 10. Patoka Dam spillway area, interpretation of subterranean features, Cavity F

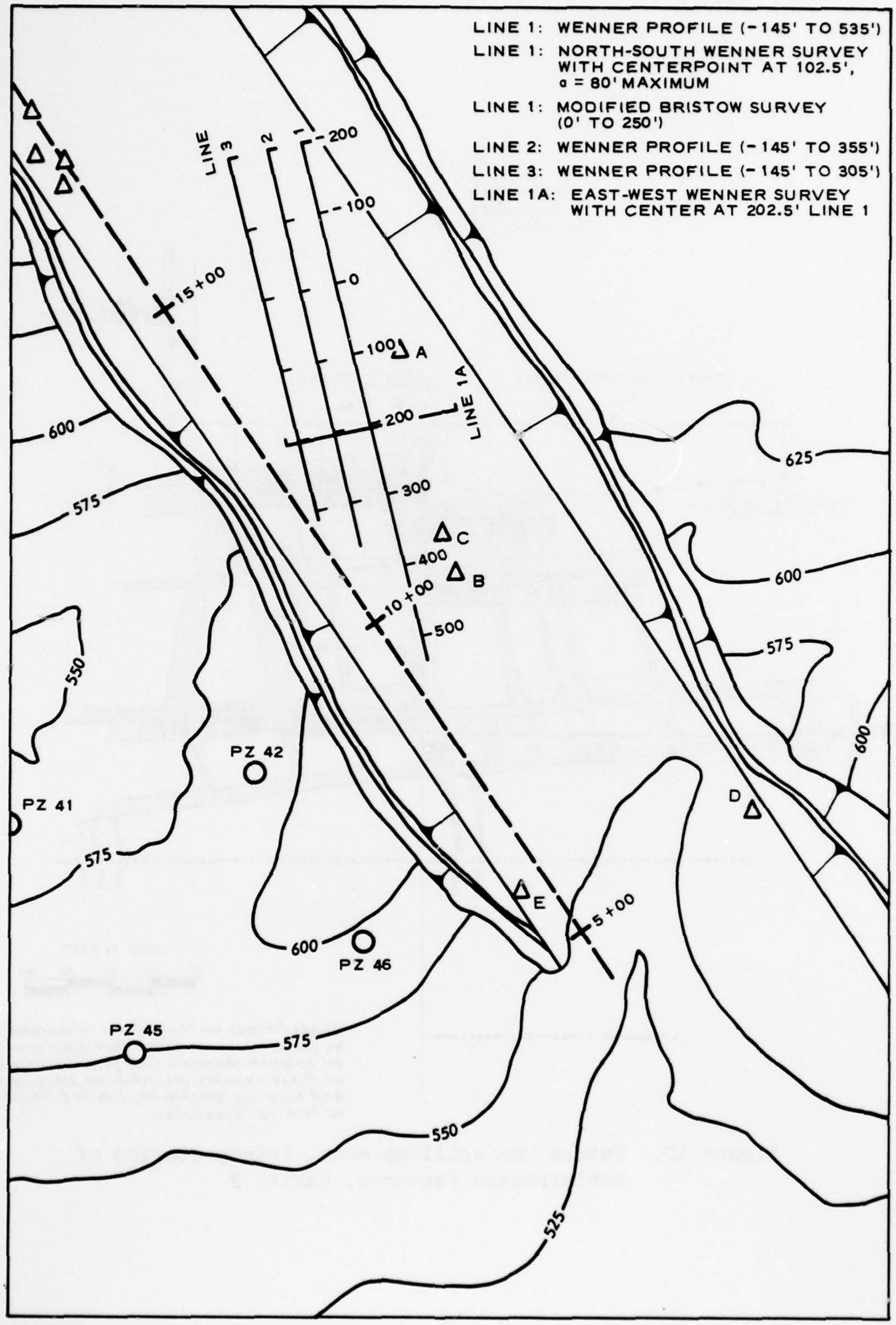

Figure 11. Location of electrical resistivity lines performed in the spillway area

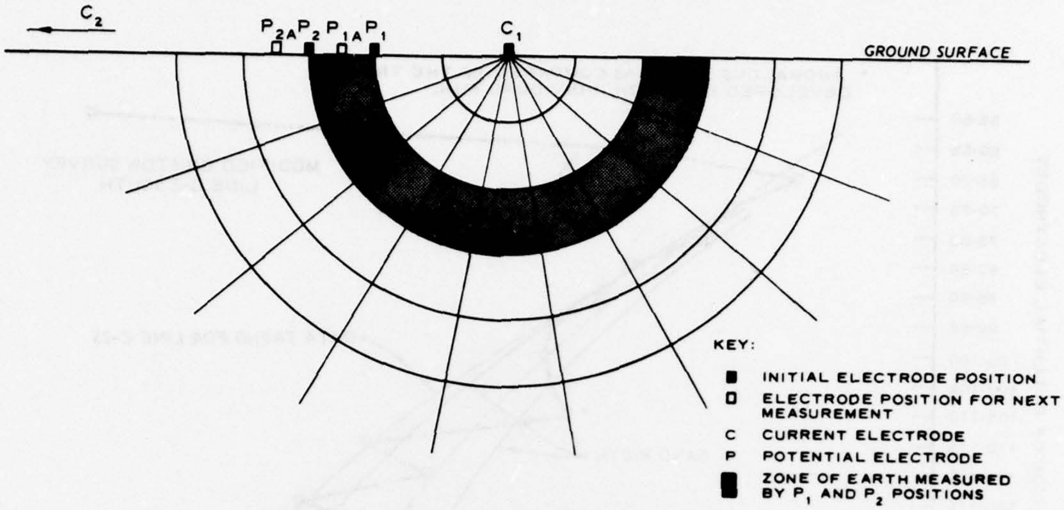

Figure 12. Bristow electrode array (after Bates)

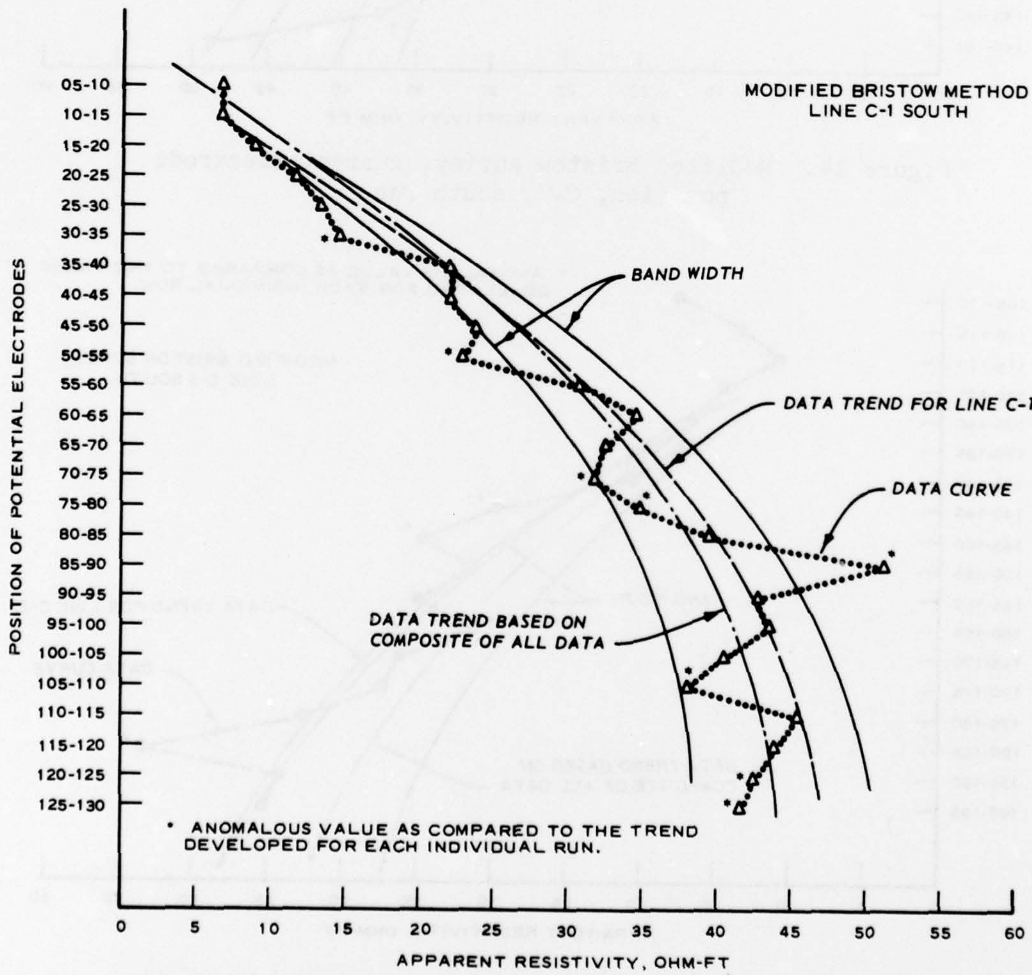

Figure 13. Modified Bristow survey, current electrode position, C-1, south run

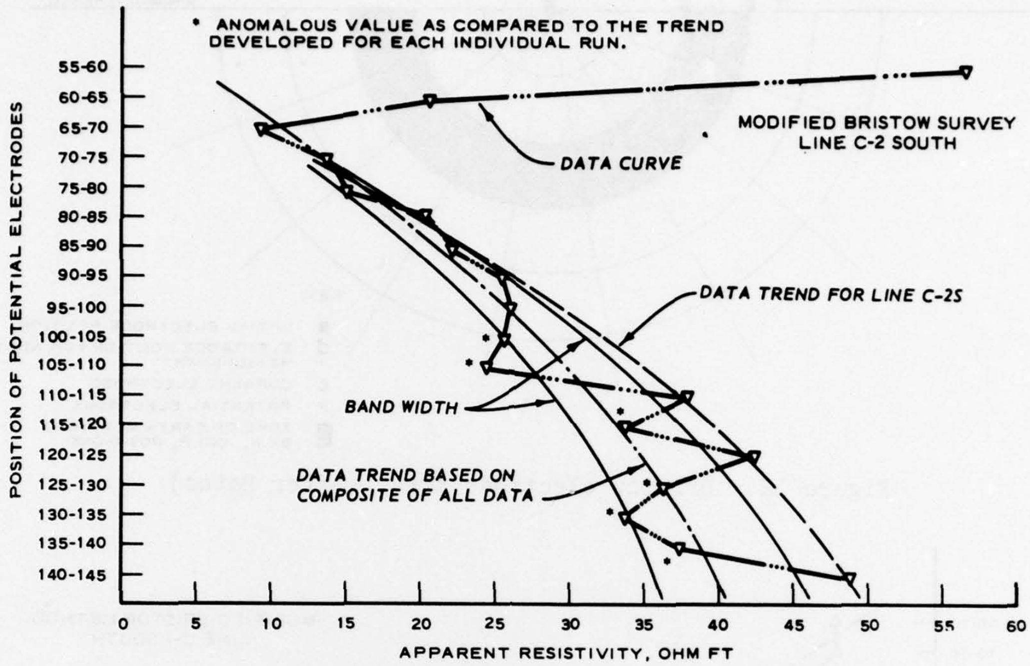

Figure 14. Modified Bristow survey, current electrode position, C-2, south run

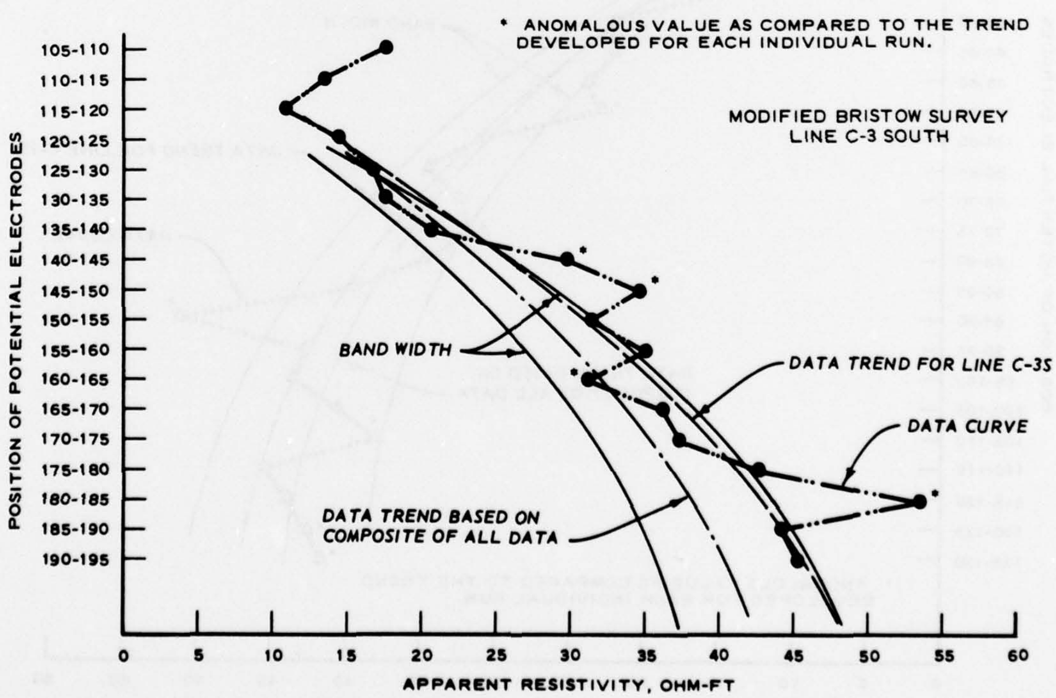

Figure 15. Modified Bristow survey, current electrode position, C-3, south run

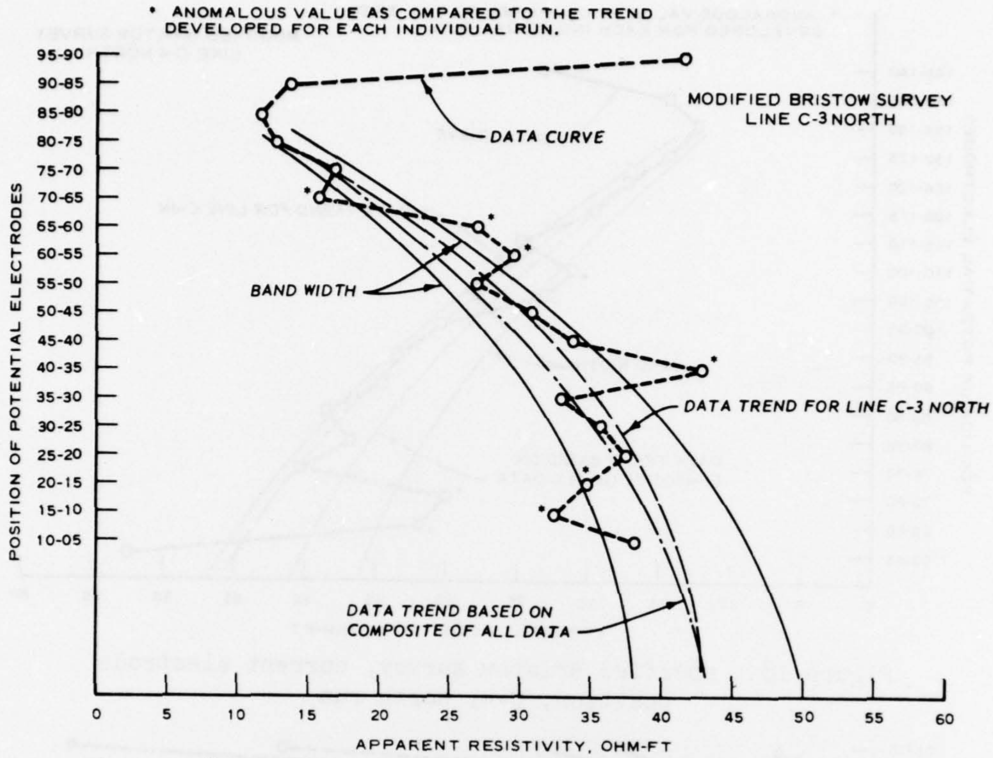

Figure 16. Modified Bristow survey, current electrode position, C-3, north run

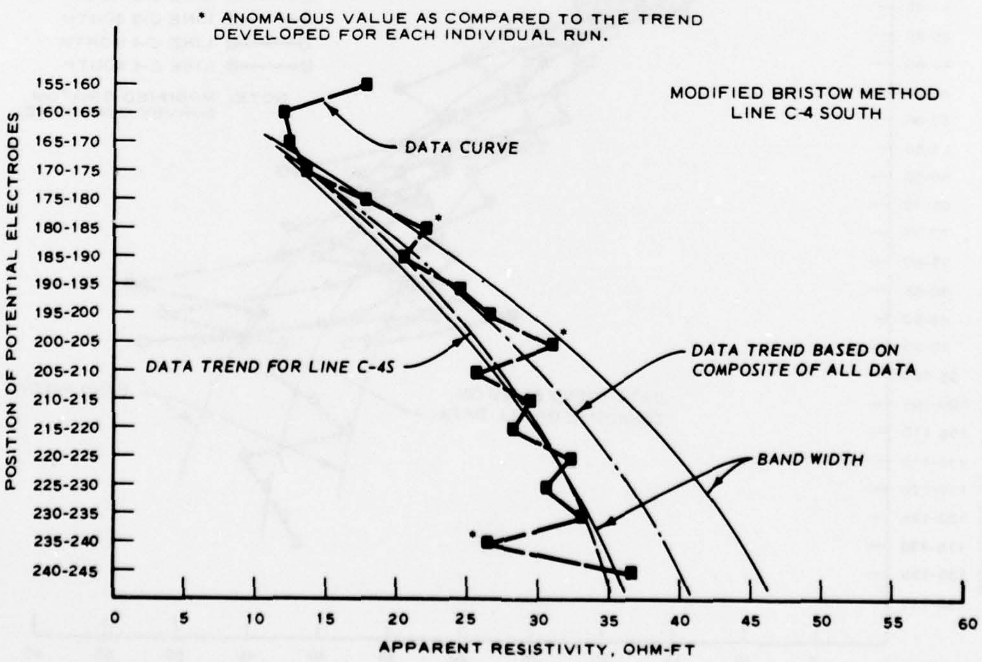

Figure 17. Modified Bristow survey, current electrode position, C-4, south run

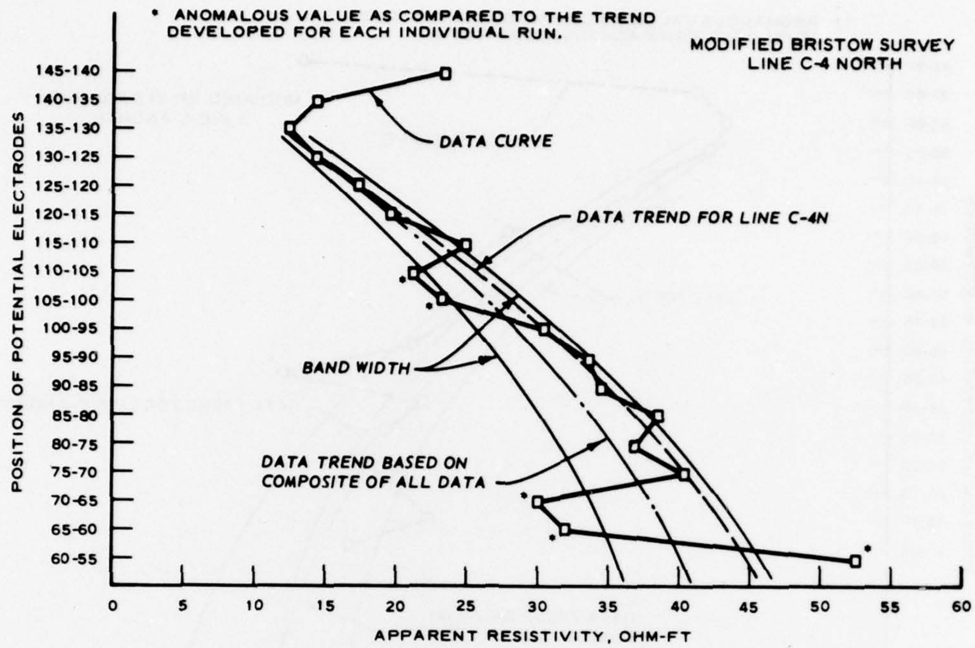

Figure 18. Modified Bristow survey, current electrode position, C-4, north run

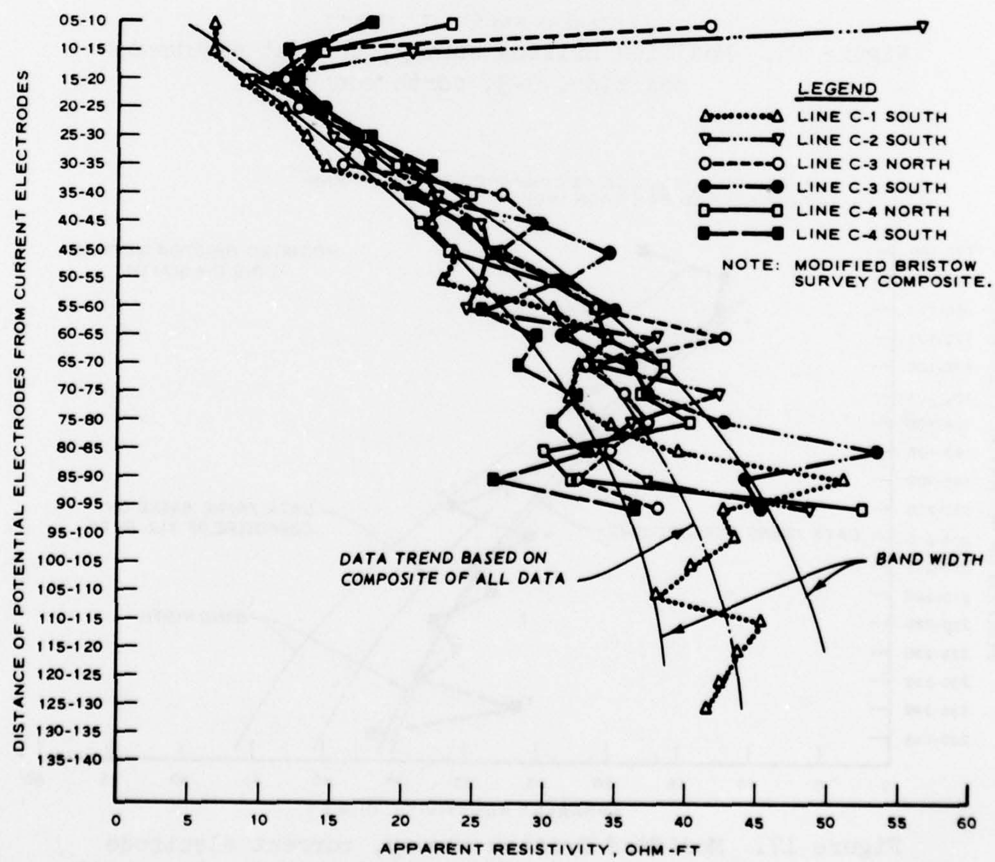

Figure 19. Modified Bristow survey, composite of all runs

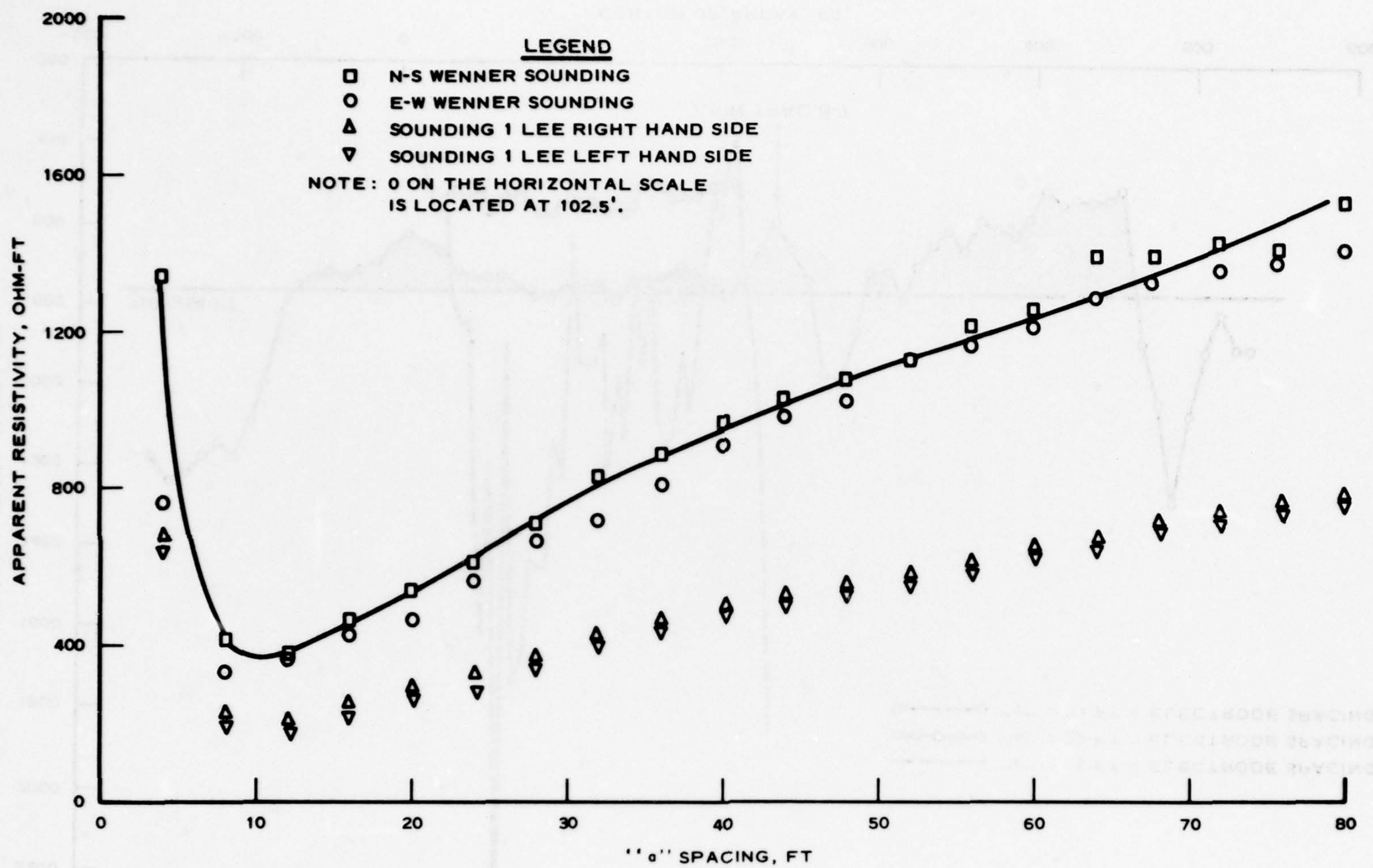

Figure 20. Plot of Wenner soundings performed in the spillway area

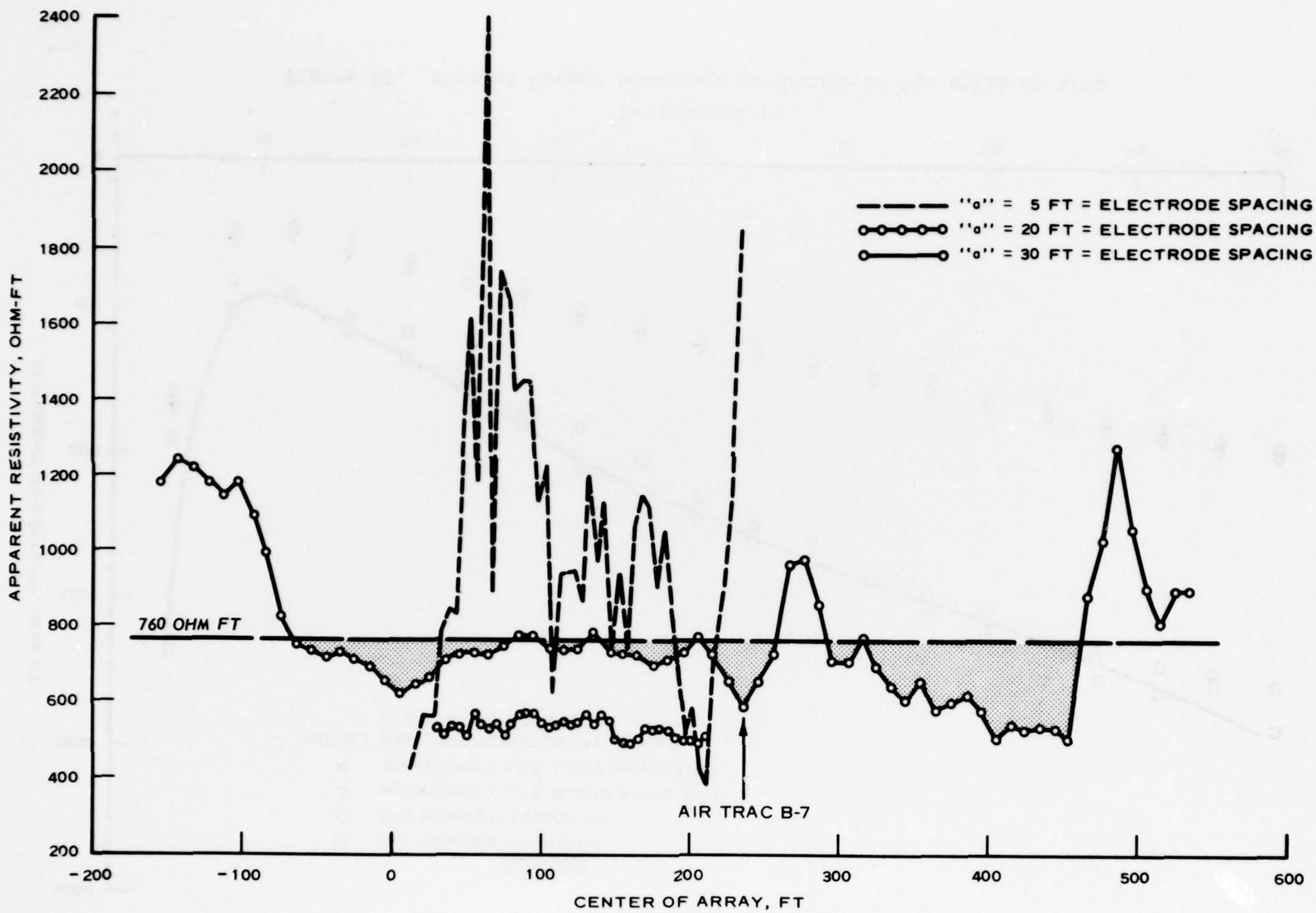

Figure 21. Wenner profile, line 1, spillway

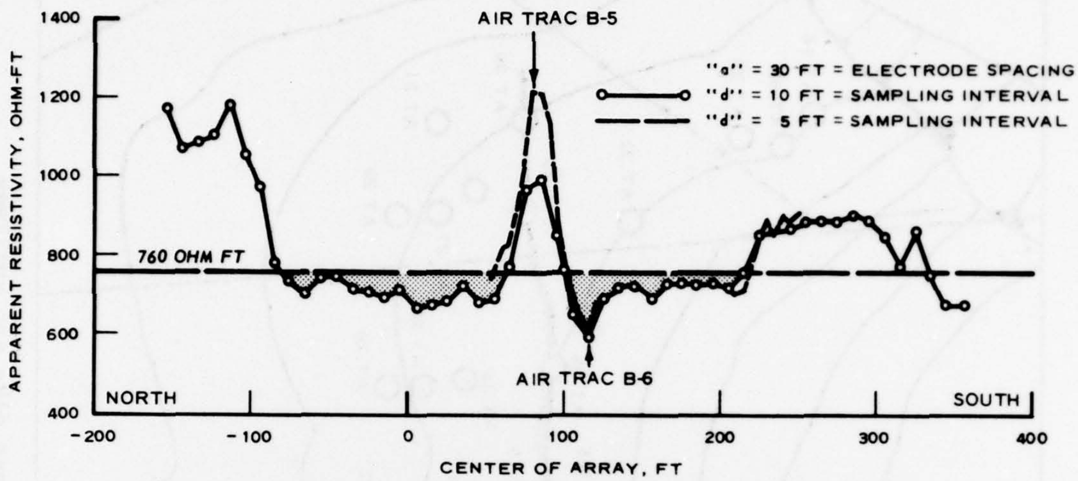

Figure 22. Wenner profile, line 2, spillway

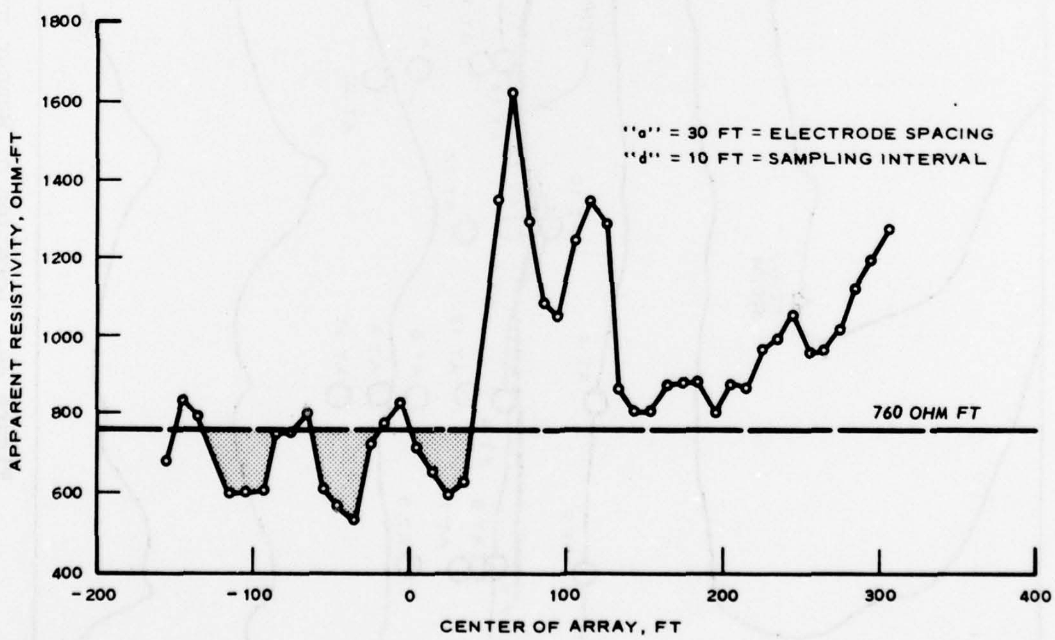

Figure 23. Wenner profile, line 3, spillway

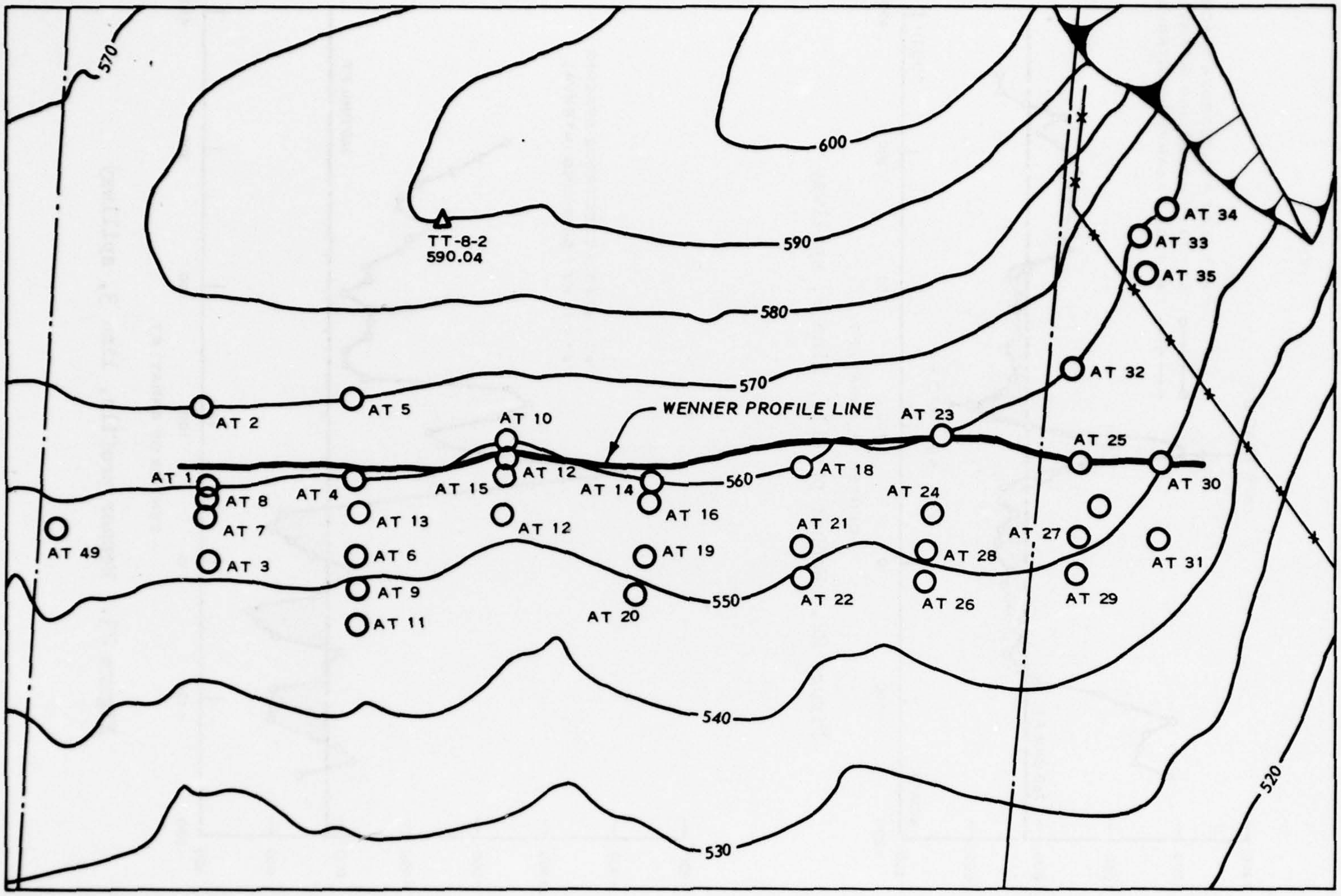

Figure 24. Location of Wenner profile between dike and spillway

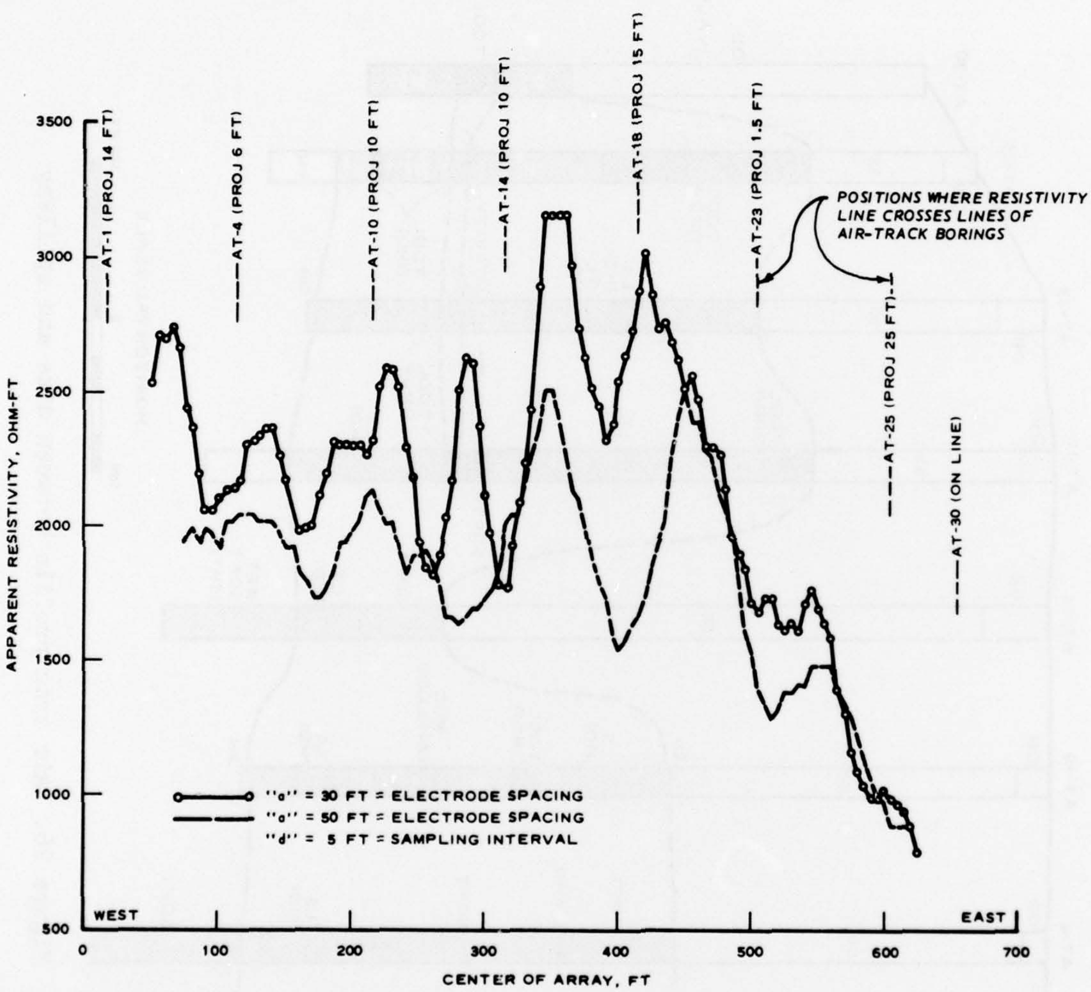

Figure 25. Wenner profile between dike and spillway, along 560 ft contour, approx

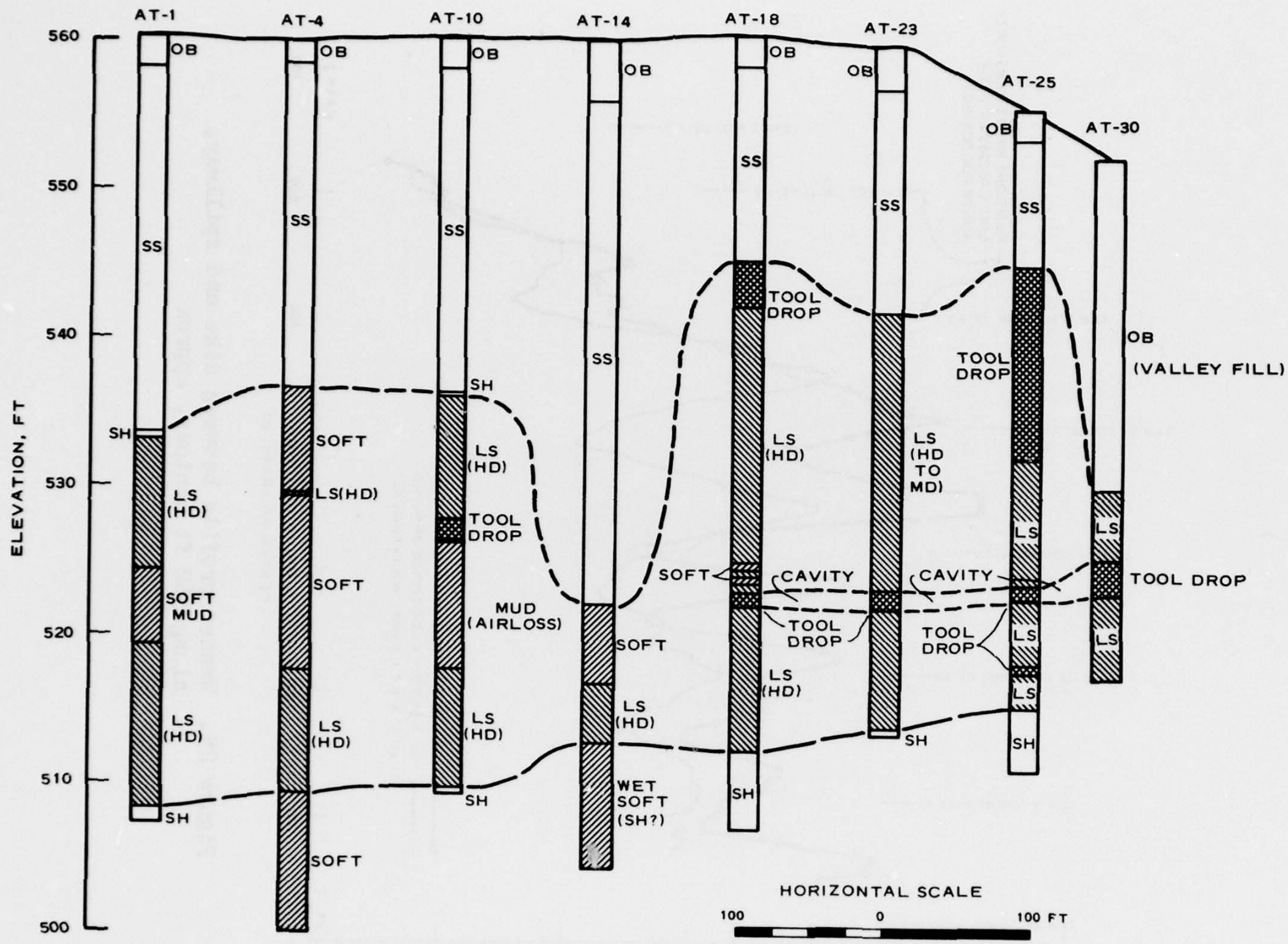

Figure 26. Air trac profile between dike and spillway

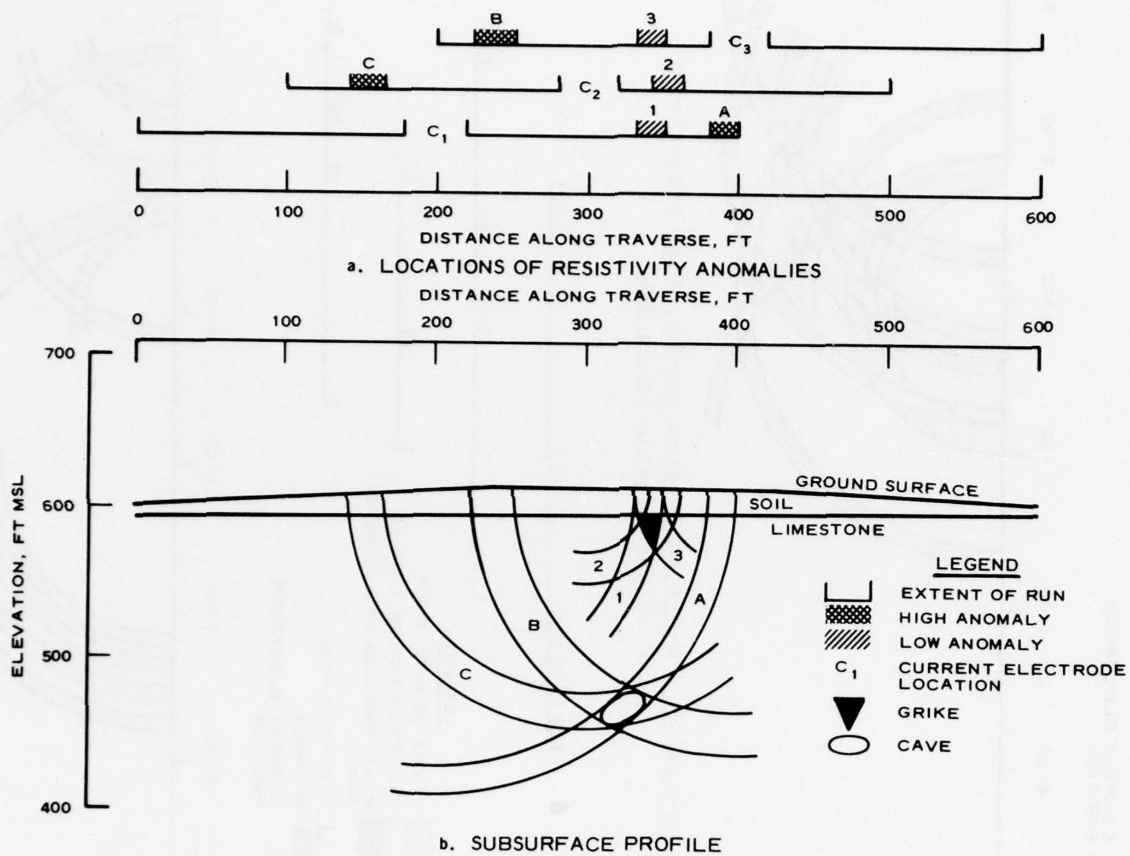

Figure 27. Simplified example of graphical solution for anomaly location (after Bates)

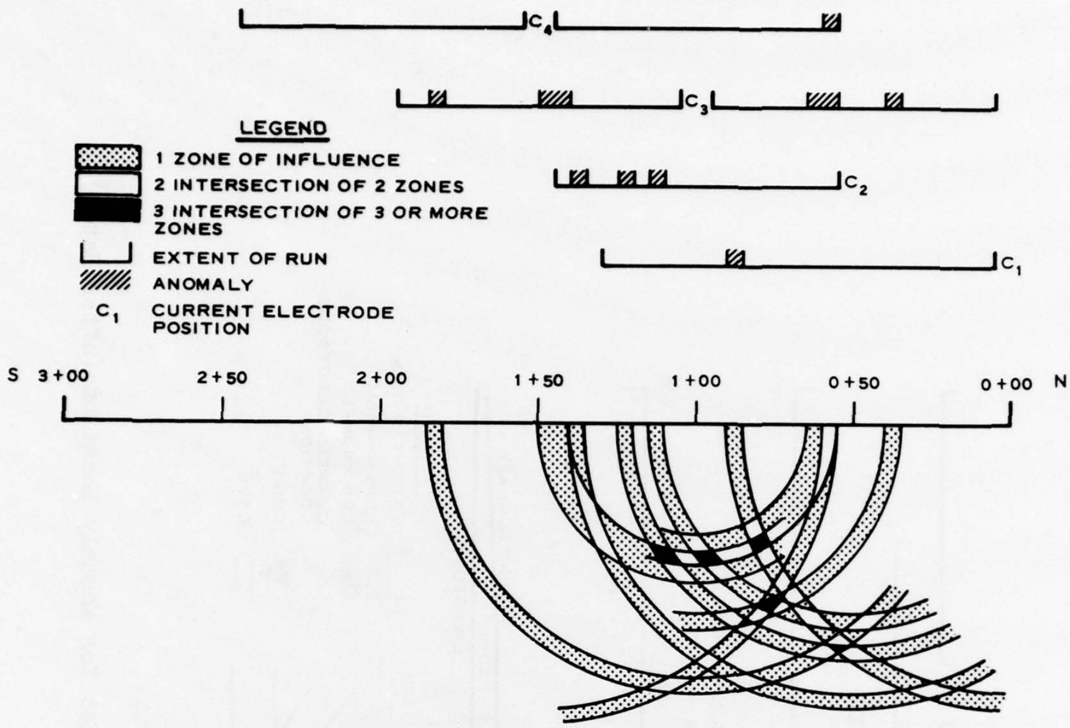

Figure 28. Modified Bristow survey, high resistivity values outside bandwidth

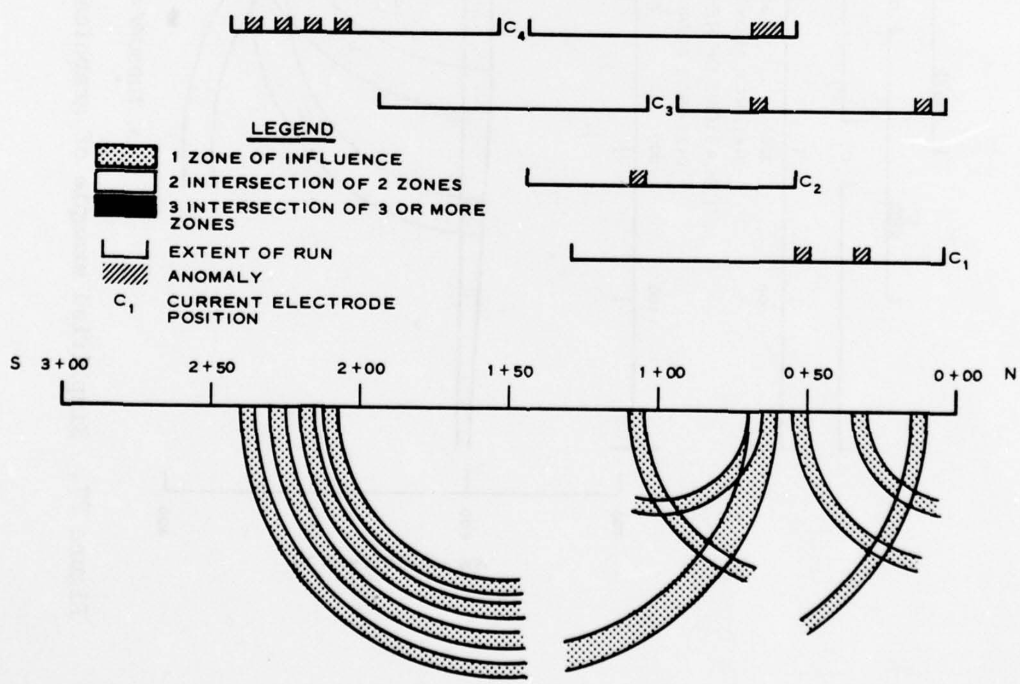

Figure 29. Modified Bristow survey, low resistivity values outside bandwidth

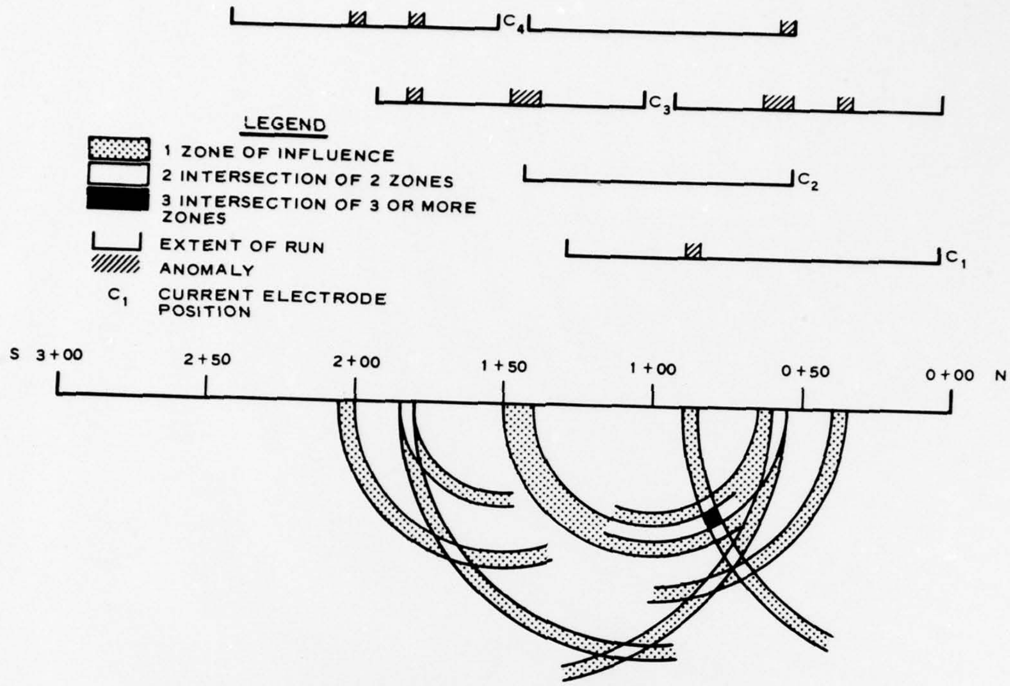

Figure 30. Modified Bristow survey, high resistivity values relative to average curve

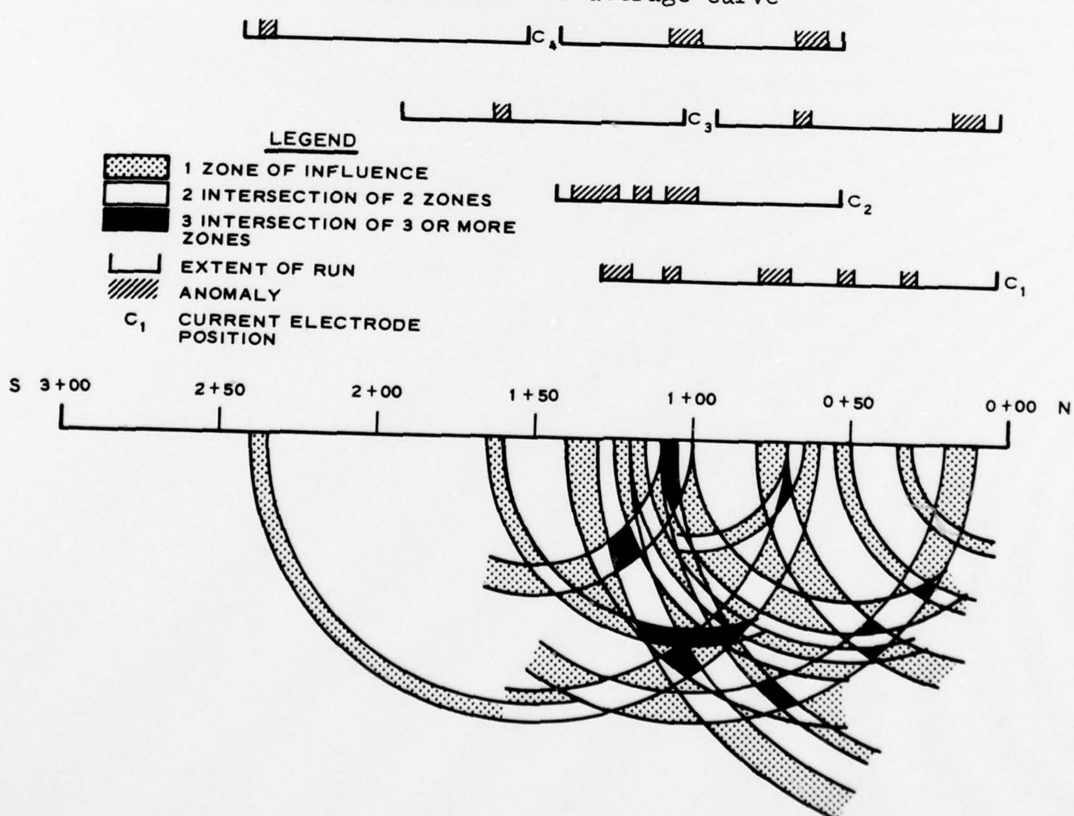

Figure 31. Modified Bristow survey, low resistivity values relative to average curve

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Cooper, Stafford S
Geophysical survey of cavernous areas, Patoka Dam, Indiana / by Stafford S. Cooper, Wayne A. Bieganousky. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1978.
25, [25] p. : ill. ; 27 cm. (Miscellaneous paper - U. S. Army Engineer Waterways Experiment Station ; S-78-1)
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